Electric vehicles and renewable energy in the transport sector - energy system consequences. Main focus: Battery electric vehicles and hydrogen based fuel cell vehicles

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Electric vehicles and renewable energy in the transport sector – energy system consequences

Main focus: Battery electric vehicles and hydrogen based fuel cell vehicles

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Abstract

The aim of the project is to analyse energy, environmental, and electricity market aspects of integrating electric vehicles in the future Danish energy system. Consequences of large-scale utilisation of electric vehicles are analysed. Furthermore, the aim is to illustrate the potential synergistic interplay between the utilisation of electric vehicles and large-scale utilisation of fluctuating renewable energy resources, such as wind power. Economic aspects for electric vehicles interacting with a liberalised electricity market are analysed. The project focuses on battery electric vehicles and fuel cell vehicles based on hydrogen.

Large-scale integration of electric, hydrogen and hybrid vehicles in the transport sector may in the future significantly reduce the emission of pollutants, and improve air quality in local and urban areas. Furthermore, through such vehicles, developments in the power supply sector may have direct implications for the road transport emissions. Options in the power sector, as to reduce CO_2-emissions in particular, may become options for the transportation sector as well.

Based on assumptions on the future technical development for battery electric vehicles, fuel cell vehicles on hydrogen, and for the conventional internal combustion engine vehicles, scenarios are set up to reflect expected options for the long-term development of the road transport fleet.

Focus is put on the Danish fleet of passenger cars and delivery vans. The scenario analysis includes assumptions on market potential developments and market penetration for the alternative vehicles. Vehicle replacement rates in the Danish transport fleet and the size of fleet development are based on data from The Danish Road Directorate. The electricity supply system development assumed is based on the Danish energy plan, Energy 21, The Plan scenario. The time horizon of the analysis is year 2030.

Results from the scenario analysis include the time scales involved for the potential transition towards electricity based vehicles, the fleet composition development, the associated developments in transport fuel consumption and fuel substitution, and the CO_2-emission reduction achievable in the overall transport and power supply system.

Detailed model simulations, on an hourly basis, have furthermore been carried out for year 2005 that address electricity purchase options for electric vehicles in the context of a liberalised electricity market. The baseline electricity market considered comprises a spot market and a balance market. The structure chosen for the baseline spot market for year 2005 is close to the structure of the Nord Pool electricity market, and the structure of the balance or regulatory market is close to the Norwegian model.

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Contents:

1 Preface

This is the final report for the project titled ‘Electric vehicles and renewable energy in the transport sector – energy system consequences’ (Eldrift og vedvarende energi i transportsektoren - konsekvenser i samspil med el- og varmesystemet). The project is carried out by Risø National Laboratory, and the project has received economic support from the Danish Energy Research Programme.

Large-scale integration of battery electric and hydrogen based fuel cell vehicles in the transport sector may in the future significantly reduce the emission of pollutants, and improve air quality in local and urban areas. Furthermore, through such vehicles, developments in the power supply sector may have direct implications for the road transport emissions. Options in the power supply sector, as to reduce CO_2-emissions in particular, may become options for the transportation sector as well.

If renewables are to contribute in large-scale to the transport energy supply, in the Danish situation it is important that wind power, and may be wave power and photovoltaic in the future, provide the main energy inputs. Hydropower is not an option in Denmark, and the Danish biomass resources available are scarce compared to the transport energy needs, as in most European countries. Furthermore, the energy efficiency of the path, via biomass to the wheel, can be less attractive. Thus, the main renewable energy inputs available are electricity based. The energy efficient electric based vehicles and drive trains therefore are important, for renewables in large-scale to provide energy to cover future road transport service needs.

Battery electric and hydrogen based fuel cell vehicles may provide a flexible energy path for the integration of a fluctuating electricity production, such as wind power, to serve transport energy needs. The vehicles may offer high energy-efficiency and very low environmental impact compared to the conventional combustion engine vehicles. Virtually no emissions to the environment occur when operating these alternative vehicles.

The overall aim of this study is to analyse such potential advantages of the alternative vehicles relative to Danish long-term aims in energy- and environmental planning, where air pollution reduction and CO_2 emission reduction are central issues.

The project is based on optimistic assumptions as far as the development and implementation of electric and hydrogen transportation technologies are concerned. It does not cover the development of regulatory instruments for this purpose.

2 Summary and conclusions

2.1 Background

Electric vehicles have gone through intensive technical development in recent years. A new generation of family class electric vehicles has now emerged on the market. With the exception of vehicle range per charge and the cost of the vehicle, these new vehicles are fully comparable with conventional passenger vehicles. Furthermore, the electric vehicle has very attractive environmental qualities, for the local environment and potentially also for the global environment. Indirect and in interplay with the power supply system the electric vehicle may contribute important CO_2 reduction in the transport sector.

The development of the electric vehicle is expected to continue. Its recent development has been pushed forward due to air pollution problems, associated with the gasoline and diesel propelled conventional vehicle, in the larger urban areas in the USA, Europe and Japan. Among the driving forces for the accelerated development are a number of national initiatives in form of research programmes, legislation etc. Furthermore, the larger car manufacturers have initiated development programmes for electric vehicles.

Legislation in California (California Air Resource Board) has reserved a future market for so-called ‘zero-emission’ vehicles, beginning year 2003, by requiring that at least 10% of all new passenger cars sold must be of such type. That translates to about 22,000 vehicles each year. The car manufactory industry in the USA direct their development efforts towards this market, but furthermore other car manufacturers e.g. from Japan aim to develop electric vehicles partly to meet this market.

National development programmes for improving battery technology for electric vehicles have been initiated both in Japan, the USA and Europe.

Hydrogen is an interesting potential future energy carrier, able to convey the use of renewable energy sources to the transport sector. However, it is still uncertain which role the hydrogen may play. The rapid and successful development of fuel cells for mobile applications is not least due to the substantial ongoing development programme ‘Partnership for a new generation of vehicles’ in the USA. Results from this programme and the ongoing research, development and demonstration also in Europe may be decisive for the future role of the direct hydrogen based vehicles.

Electric vehicles constitute a new category of consumers on the electricity market, which possess considerable load management ability. Electric vehicles recharging in peak load periods may cause complications for the power supply, by increasing the need for power production capacity in the system. If however, recharging is displaced to the low load periods or periods of low electricity prices, e.g. via recharging in the night period, a considerable electricity demand increase to serve a fleet of electric vehicles may be covered from the existing supply system. By appropriate system integration, the electric vehicles can contribute considerable flexibility to the system, due to its load management ability, which increases the overall system capability as to integrate fluctuating energy sources such as wind power.

2.2 Aim of the study

The overall aim of the study is to analyse options for achieving air pollution reduction and CO_2 emission reduction in the road transport sector. The options studied concern the transition towards integration of battery electric vehicles (BEV), and fuel cell vehicles based on hydrogen from electricity (HFCV), and the gradual phasing out of the conventional internal combustion engine vehicle (ICEV).

The study focuses on the potential interplay between the transport sector and the power supply sector. Energy sources entering the electricity supply can through such vehicles become available to serve road transport needs in the future. The energy source flexibility and CO_2 reduction options in the electricity system become options for the transport sector.

Scenarios for BEV and HFCV integration are set up in order to analyse long-term consequences, if large-scale efforts are carried out to substitute the conventional internal combustion engine vehicle with such alternative vehicles. The analysis concentrates on such substitution options in the Danish transport segments: Passenger cars and delivery vans of weight less than 2 tons.

Consequences focussed on in the scenario analyses are the potential energy substitution effects, and CO_2 emission reduction achievable. It is an aim to estimate the time scales involved for such efforts to have effect. Furthermore, the electricity demand increase, to operate the electricity based road transport fleet in the scenarios, is compared to Danish wind power production capacity.

2.3 Scenario analyses

Three scenarios, designated S1, S2, and S3 are set up as follows:

S1: BEV scenario.
Aims to integrate most energy efficient technology and to achieve maximum fossil fuel substitution and CO_2 emission reduction per vehicle.
The battery electric vehicle technology, being the most energy efficient among the technologies considered, is promoted for rapid transport fleet integration.
Limited range of the BEV limits the market potential. Year 2030 about 40% of the fleet or about 1 million vehicles are aimed to become BEVs in the scenario.

S2: HFCV scenario.

Aims to integrate energy efficient technology, with range per refill fully comparable to the conventional ICEV, to achieve fossil fuel substitution and CO_2 emission reduction.

The direct hydrogen fuel cell vehicle technology compared to the ICEV, is expected to offer energy efficiency and CO_2 emission gains beyond year 2010, and from then of the vehicle is promoted for rapid transport fleet integration.

Infrastructure build up for hydrogen production and tanking is needed. Year 2030 about 40% of the fleet or about 1 million vehicles are aimed to become HFCV in the scenario.

S3: Combined BEV & HFCV scenario.

Aims to minimise CO_2 emission and consumption of fossil fuels in the road transport sector via promoting high market penetration of the electricity based alternative vehicles.

The scenario aims to half CO_2 emission by year 2030 relative to the baseline development for the road transport segment considered.

The S3 scenario is the composition of the S1 and S2 scenarios. Year 2030 about 80% of the fleet or about 2 million vehicles are aimed to become electricity-based vehicles, BEV or HFCV.

All scenarios are related to the long-term forecast [4] from The Danish Road Directorate, Ministry of Transport, as the reference development for the Danish transport fleet.

The Danish energy plan Energy21, The Plan scenario [2], forms the basic assumptions for the power supply system development in the analyses. Due to quite low replacement rates for passenger vehicles in the road transport sector, long-term development aspects up to year 2030 are analysed.

It is assumed that the vehicle cost for consumers at the time of its introduction in the scenarios is not prohibitive for a large-scale application. A persistent and forward-looking policy to support the integration of these new vehicles is implicitly assumed.

2.4 Results and conclusions

From the project results the following conclusions are drawn. These are sorted according to the main sections in the report, covering *technical development* of the individual vehicles, *scenario analyses* for the Danish situation and *power system integration.*

2.4.1 Technical development

For the defined average vehicle in the Danish transport segment, passenger cars and delivery vans (of weight less than 2 tons), the assumed development in the specific energy consumption and CO_2 emission for new ICEV, BEV and HFCV are summed up in Table 2-1.

For the BEV and HFCV the local emissions to the air of pollutants are virtually zero. Here, only the CO_2 emission in the overall energy system is considered.

The BEV and HFCV energy supplies are based on electricity from the Danish grid. It has been assumed that hydrogen to operate the direct hydrogen fuel cell vehicle is produced via electrolysis with an overall conversion efficient on energy basis, from grid electricity to hydrogen stored onboard the vehicle, is 85% generally.

From Table 2-1 it is seen that for the ICEV only a moderate reduction in the specific consumption of gasoline per km driven in the fleet average vehicle is expected [4] during the period. The defined fleet average vehicle is seen to require about twofold the fuel of the so-called ‘3litre’ ICEV (33km/litre) vehicle. Likewise for the emission of CO_2.

Comparing the BEV and HFCV it is seen from the table that using the HFCV the expected CO_2 emission is more than twofold the expected emission from the comparable size BEV. This reflects the potentially very efficient energy path, from electricity to wheel, of the BEV.

Table 2-1. Vehicle energy efficiency and specific CO_2 emission. Comparison for defined average fleet vehicle of type ICE, BEV, and HFCV. Power supply according to Energy21, The Plan scenario.

Type of vehicle Size: Average fleet	1997/2000	2005/2010	2025/2030
ICEV Reference			
$kWh_{gasoline}/km$	0.66	0.55	0.55
gCO_2/km	176	150	150
ICEV ‘3litre aim’			
$kWh_{gasoline}/km$	-	0.27	0.27
gCO_2/km	-	72	72
BEV			
$kWh_{electricity}/km$	0.24	0.13	0.10
gCO_2/km	156	63	19
HFCV			
$kWh_{hydrogen}/km$	-	0.32	0.24
gCO_2/km	-	181	53

Compared to the conventional ICEV, the battery electric vehicle (BEV) is very attractive from both an energy efficiency and CO_2 emission point of view. The CO_2 emission may have dropped to almost 1/3 of the expected average ICEV for new BEVs entering the fleet in the period 2005 to 2010. This is less than the CO_2 emission of the ‘3litre’ vehicle.

BEVs entering the fleet in the period 2025 to 2030 have considerable lower CO_2 emission than the ICEV. Furthermore, the BEV vehicles that are in the fleet, improve CO_2 characteristics, due to the power supply system development along the vehicle lifetime. The combination of the Danish power supply system development towards reduced CO_2 emission per kWh and the technical development of the BEV result in very low BEV long term specific CO_2 emission.

The HFCV, that match the ICEV in fast refill and range per refill, will not from a CO_2 reduction point of view match the ICEV before 2010, when the hydrogen is produced via electrolysis in the Danish system. The HFCV though is very attractive relative to reducing road traffic air pollution. If the hydrogen is produced from e.g. methanol or gasoline, the reformer based HFCV can have low CO_2 emission compared to the average ICEV. Seen from both the emission and energy resource perspective, the development of HFCV is very positive relative to the ICEV.

Based on the assumptions, the HFCV becomes CO_2-attractive relative to ICEV beyond year 2010. HFCVs entering the fleet in the period 2025 to 2030 have considerable lower CO_2 emission than the average ICEV. This difference is about 1:3 as seen from Table 2-1.

2.4.2 Scenario analyses

The main results from the scenario analyses are shown in Table 2-2. The main results focussed on are the fleet development for electric based alternative vehicles, substituted fuel in the scenarios relative to the baseline development, and the overall system CO_2 emission consequences.

Table 2-2. Main results for scenarios S1, S2, and S3, year 2015 and 2030. Danish transport sub-sector: Passenger cars and delivery vans <2 tons. Power supply according to Energy21, The Plan scenario.

Scenario	**S1**		**S2**		**S3**	
Year	2015	2030	2015	2030	2015	2030
Transport fleet developed						
BEV&HFCV, # vehicles	337.000	930.000	93.000	980.000	430.000	1910000
Fuel/Power substitution						
ICEV fuel substituted,TWh	3.86	10.14	1.06	10.69	4.92	20.83
El. demand increase, TWh	0.94	1.90	0.66	5.40	1.60	7.30
Overall CO_2 reduction						
1000 tons CO_2/year	599	2168	-4	1471	595	3640
% of sub-sector	9%	30%	-0%	20%	9%	50%
% of total transport	5%	15%	-0%	10%	5%	26%

Fuel substitution shown in Table 2-2 relates to the transport sector, where the consumption of conventional fuels, gasoline and diesel (expressed in TWh in the table), is reduced on the expense of an increased consumption of electricity, to operate BEV and HFCV fleets.

The alternative BEV and HFCV fleets provide the same transport services as the respective baseline or reference ICEV fleets. The overall transport service produced is unchanged going from the baseline situation to the alternatives.

From the table it is seen that the BEV alternative is considerable more energy efficient than the baseline ICEV. The S1 scenario year 2030 shows that the BEV fleet using 1.90 TWh of electricity (ab grid) may substitute 10.14 TWh of conventional fuel (gasoline/diesel). Taking into account, that such comparison involves the two energy qualities, electricity and gasoline/diesel, this still reflects the considerable energy efficiency difference between the new BEV drive train and the conventional ICEV drive train. It must be emphasised, however, that the conventional ICEV defined in the baseline development [4] is the expected development for ICEVs in the Danish fleet, and not an ICEV development optimised for energy efficiency, as described in section 4.1.

The BEV and HFCV alternatives offer zero emission of air pollutants during operation, and CO_2 emission reduction potentials, according to the CO_2 characteristics of the power supply system in question.

The CO_2 emission reduction consequences shown in Table 2-2 are based on the assumption, that the CO_2 characteristics of electricity during the period analysed develop in accordance with the power supply system described in Energy21, The Plan scenario [2].

Relative to the baseline CO_2 emission from the transport sub-sector considered, passenger cars and delivery vans <2 tons, the S3 scenario may provide a 50% reduction of the CO_2 emission by year 2030, as seen from the table.

This reduction amounts 3.6 million tons CO_2/year. Relative to the expected baseline emission from the Danish transport sector in total, the S3 reduction amounts to 26%, as seen from Table 2-2.

Year 2015 the S3 scenario may contribute an about 5% reduction in CO_2 emission from the Danish transport sector in total.

2.4.3 Power system integration

Simulation of BEVs interacting with a defined electricity market, year 2005, has been carried out. The set up baseline electricity market comprises a spot market and a balance market for electricity. The structure chosen for the baseline spot market for year 2005 is close to the structure of the existing Nord Pool electricity market and the structure of the balance or regulatory market is close to the existing Norwegian model.

The following conclusions are drawn from the analyses:

- EV charging in the daytime must be avoided due to peak load constraints in the electricity transmission and distribution system, and in the production system. Such constraints are reflected in electricity spot market prices. Typically, EV recharging will take place in the low load periods when electricity prices are low, e.g. during the night. Off-peak power transmission capacity, to support increased loads in the scenarios by year 2030, can be met in the present system.

- Two-way communication systems, between consumers and the power exchange, and electricity metering by the hour can generate benefits both for consumers and for the power system balance. Such systems may mobilise regulation capability from the demand side of the system in general. The power balance may benefit from reduced/postponed capacity investments, and the consumers may gain lower prices. EV owners that have considerable load flexibility may in particular gain from such systems.

- Load flexibility of the BEVs allows for postponing battery recharge to the low load periods with favourable spot market prices. Compared to the average spot market price, the BEV load flexibility may reduce the annual average electricity purchase costs of about 5% (tax excluded).

- If furthermore, the BEV owners have access to the electricity trade at the balance market a cost reduction of about 10% relative to the average spot market price can be achieved in average on an annual basis. This, assuming a battery capacity able of about 200km/charge.

When the EV owner can achieve an overall gain from trading at the balance market, the supply of power regulation capability on the balance market increases from such trade.

As the EV fleet increases the power regulation capability consequently increase. EVs increase the regulation capability in the overall power system, and thus increase the ability of the system to integrate a fluctuating electricity production such as wind power.

Offshore wind power and electric vehicles

If the additional annual electricity demand to operate the BEV and HFCV fleets in the scenarios is to be generated from Danish offshore wind turbines the corresponding wind power capacity increase will be as shown in Figure 2-1.

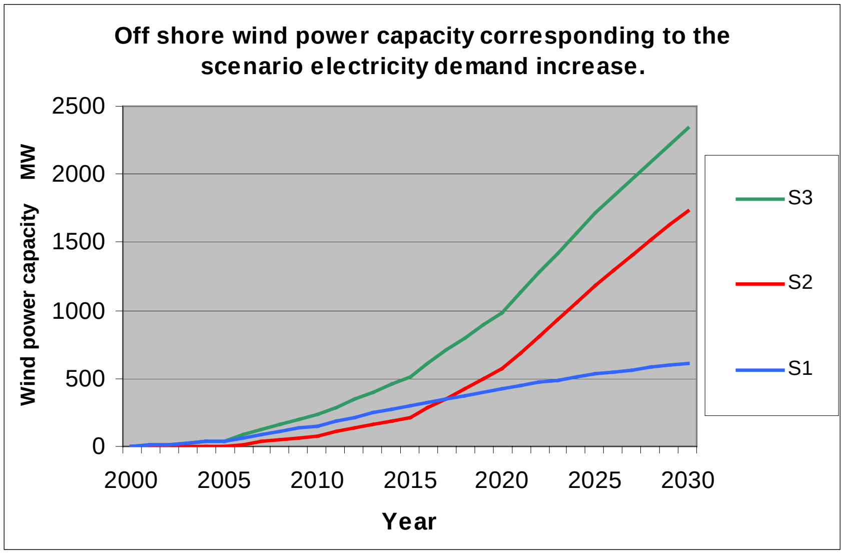

Figure 2-1 Wind power capacity offshore, able to produce the energy equivalent of the electricity demand increase resulting from the scenarios S1, S2, and S3.

The corresponding wind power capacity needed to produce the electricity associated with operating the individual (average fleet) electric vehicle on an annual basis is shown in Table 2-3.

Table 2-3 Wind power capacity needed to generate the energy, equivalent to the annual demand of the average, electricity based vehicle. Assumed that electricity for transport is generated from offshore wind power.

Wind capacity per vehicle	**S1**	**S2**	**S3**
	kW/car	kW/car	kW/car
2005	1.44	..	1.44
2015	0.90	2.26	1.19
2030	0.66	1.77	1.23

From the table it is seen, that the average BEV vehicle year 2030 on an annual basis consumes electricity equivalent to the production from approximately 0.66 kW installed wind power capacity offshore. This may be compared to the capacity for residential recharge of the BEV of 10kW/car typically.

Hydrogen to serve the corresponding size HFCV vehicle could be produced from the electricity generated by approximately 1.8 kW of installed wind power capacity, in Danish offshore wind conditions.

3 Introduction

The study addresses options for future utilisation of battery electric vehicles (BEV) and hydrogen based fuel cell vehicles (HFCV) for road transport. The main focus is put on the interplay between the transport sector and the power supply sector that may arise via such vehicles, when electricity from the Danish grid is to supply the transport energy inputs.

Structure of the analysis

The study is carried out as a scenario analysis that is structured in three main sections. These concern the:

- *Technical development* of battery electric vehicles (BEV), direct hydrogen fuel cell vehicles (HFCV), and the conventional internal combustion vehicle (ICEV).
  (Chapter 4)
- *Scenario analysis* of large-scale introduction of battery electric vehicles and direct hydrogen fuel cell vehicles in the Danish road transport sector, and
  (Chapter 5)
- *Power system integration* aspects, and analysis of the interaction between electric based vehicles and the power supply system via a power exchange.
  (Chapter 6)

The main aspects covered in these sections are the following:

Technical development

Expected developments in energy efficiency for the BEV, HFCV and ICEV are described. The long-term energy efficiency gains expected via the BEV and HFCV relative to the average conventional ICEV are adressed, and gasoline/diesel substitution associated with a transition towards electricity and hydrogen based transportation is described.

The CO_2 emission characteristics of the BEV, HFCV and ICEV are adressed, and expected future developments are compared. Options for achieving emission reductions in the road transport sector are described, taking into account the Danish power supply system development, according to Energy21, The Plan scenario.

Scenario analysis

Based on assumptions on the future technical development for battery electric vehicles, fuel cell vehicles on hydrogen, and for the conventional internal combustion engine vehicles, scenarios are set up to reflect expected options for the long-term development of the road transport sector.

The scenarios aim to illustrate options for achieving air pollution reduction and CO_2 emission reduction in the transport sector. Time scales involved for integration of BEV and HFCV vehicles are described, taking into account the potential market development for the alternative vehicles, and the expected lifetime of vehicles in the Danish road transport fleet.

Three scenarios designated S1, S2, and S3 for large-scale integration of electricity based vehicles are set up with the following aims:

S1: BEV scenario.
Aims to integrate most energy efficient technology and to achieve maximum fossil fuel substitution and CO_2 emission reduction per vehicle.

S2: HFCV scenario.
Aims to integrate energy efficient technology, with range per refill fully comparable to the conventional ICEV, to achieve fossil fuel substitution and CO_2 emission reduction.

S3: Combined BEV & HFCV scenario.
Aims to minimise CO_2 emission and consumption of fossil fuels in the road transport sector via promoting high market penetration of the electricity based alternative vehicles.

All scenarios include the long-term forecast from The Danish Road Directorate, Ministry of Transport [4], as the reference development for the Danish transport fleet.

The Danish energy plan, Energy21, The Plan scenario [2], forms the basic assumptions for the power supply system development in the analysis. Development aspects up to year 2030 are analysed.

Power system integration:

Power transmission and distribution capacity in the Danish grid are compared to demands of the scenarios S1, S2 and S3.

Furthermore, the ability of the electricity based BEV and HFCV vehicles as to utilise a fluctuating electricity production, such as wind power is adressed. Load management options offered by a BEV or HFCV fleet are adressed. The relevance of introducing metering by the hour and a two-way communication system to continously inform consumers on the electricity price development is discussed as a mean to mobilise the load management options as elements in the power system regulation. Potential BEV interaction with a liberalised power exchange as to supply power regulation to the market is described, and achievable gains for the EV owner on a set up baseline power exchange are described.

Furthermore, the wind power capacity needed to generate the energy required to operate the BEV and HFCV fleets in the scenarios is described.

4 Battery and fuel cell vehicles compared to ICE vehicles

The alternative road transport vehicles considered here, battery electric vehicles (BEV) and direct hydrogen fuel cell vehicles (HFCV) generate virtually no air pollutants when operated. Substituting the conventional internal combustion vehicle by such alternative vehicles the main consequences for emissions to the air concern the

- Emissions of toxic air pollutants to the local environment and
- Emission of greenhouse gasses, and in particular emission of CO_2, related to the energy chain fuelling the vehicles.

The considered alternative vehicles themselves do not emit toxic air pollutants. However, emissions from the energy conversion paths applied to generate electricity and/or hydrogen to operate the alternative vehicles may involve emissions at the generating facilities and in quantities depending on the energy conversion path in question and the applied emission removal techniques.

The emission of CO_2 is addressed in this study. The study is limited to the analysis of the energy paths, where electricity from the grid supply BEV charging and is the base for hydrogen production to operate HFCV. Characteristics of the electricity supply system and its expected future development will be based on the Danish situation. The expected Danish power system development according to Energy21, the Plan up to year 2030 forms the basis for the analysis.

The specific energy consumption and CO_2 emission of the battery electric vehicle, the direct hydrogen fuel cell vehicles, and the conventional ICE vehicle are compared. This comparison is based on a defined average vehicle, which represents the typical size (four-seat family) passenger car or delivery van in the present Danish fleet. Data described in this section, for the development of the individual vehicles form part of the basis for the further scenario analyses.

4.1 Specific energy consumption for BEV, FCEV and ICE vehicles

The transport fleet segments focussed on consist of passenger cars and delivery vans of weight less than 2 tons. This segment is consistent with definitions used in the Danish statistics. About half of the total transport energy used in Denmark relates to this segment (see Figure 5-1).

Covering this segment, the average new car entering the Danish fleet is defined, for the particular year or vintage in question. These average cars are defined in their conventional ICE version with respect to their specific fuel consumption and the expected development in energy efficiency up to year 2030. This description of the fleet segments reflects the reference development expected in the Danish fleet.

The reference development in energy efficiency for the defined average conventional ICE vehicle will be compared to an expected development for the alternative vehicles.

4.1.1 Internal combustion engine vehicle (ICEV)

As the starting point of the analysis, forecasts of the development in transport work and fleet size up to year 2030 from the Danish Road Directorate, Ministry of Transport [4], are assumed.

From these forecasts an implicit expected reference development for the specific energy consumption can be derived for new cars entering the fleet during the period. For this derivation it has been assumed, that the replacement rates for vehicles in the segment analysed in the Danish transport fleet is as shown later in Figure 5-10 throughout the period.

The development for the specific energy consumption for new internal combustion engine vehicles (ICEV) on average entering the fleet is shown in Figure 4-1. In the further analysis this expected development constitutes the reference. It covers the average new ICEVs entering the Danish fleet in the period up to year 2030.

From Figure 4-1 it is seen, that only a moderate change in the mileage for the average future ICEV is expected. The average cars in the fleet today (until year 2000) have a specific energy consumption of about 0.66 $kWh_{gasoline}$/km or about 14km/litre as shown in the figure.

A decrease of about 17% from the present level to the year 2010 level is expected in the reference case development. Beyond year 2010 the specific energy consumption of new cars has been assumed to be constant in the reference.

The reference development assumed may not reflect the best available technology on ICE vehicles and gasoline based hybrid electric vehicles. Some car manufacturers market today or have announced soon to market family class vehicles that offer a range of 100km on 3litre of gasoline (33km/litre and about 80MPG). This is equivalent to 0.277 $kWh_{gasoline}$/km in Figure 4-1. Thus such vehicles will have a specific energy consumption that is about half of the expected level for the fleet average ICE vehicle in the reference development beyond year 2010.

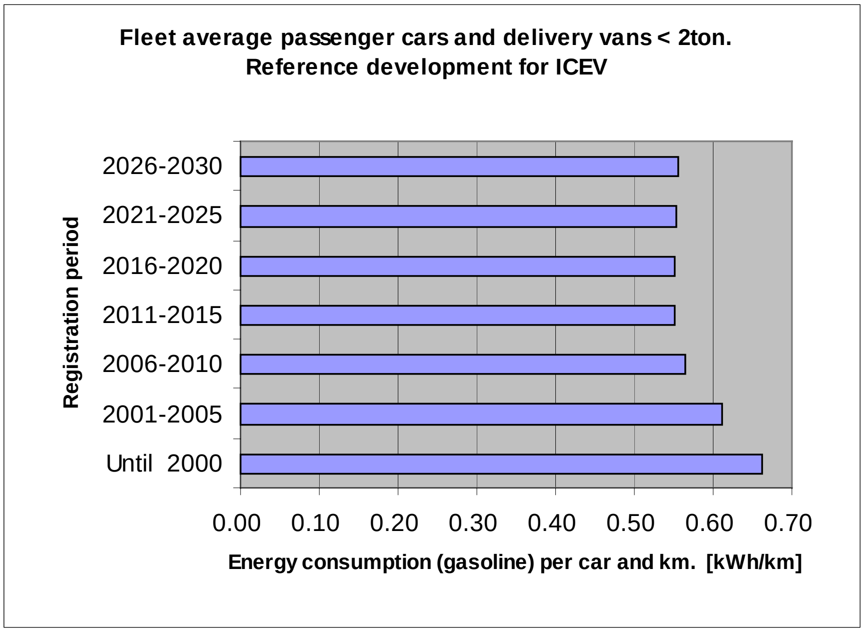

Figure 4-1 Specific energy consumption assumed for future ICE vehicles. Passenger cars and delivery vans <2 tons. Based on forecasts on transport work and fleet size development from the Danish Road Directorate, Ministry of Transport. Units: $kWh_{gasoline}/km$.

4.1.2 Battery electric vehicle (BEV)

The drive train of the battery electric vehicle (BEV) has the potential to become very energy efficient. Corresponding to the defined average vehicle, described in its ICEV version in the previous section, the assumed specific energy consumption for the BEV development is shown in Figure 4-2.

Improvements of the BEV technology during the period are expected to reduce the specific energy consumption considerable for the BEV marketed. The energy efficiency increase is expected to result from a combination of improvements. These include improved battery energy efficiency, BEV motor and transmission efficiency, and a reduction in weight of the future BEV.

Beyond year 2015 it is assumed that the specific energy consumption of the BEV is 0.10 kWh_{el}/km. Thus, the electricity consumption is expected reduce to less than half the present level, despite the range per charge is assumed to increase during the same period (see Figure 5-5).

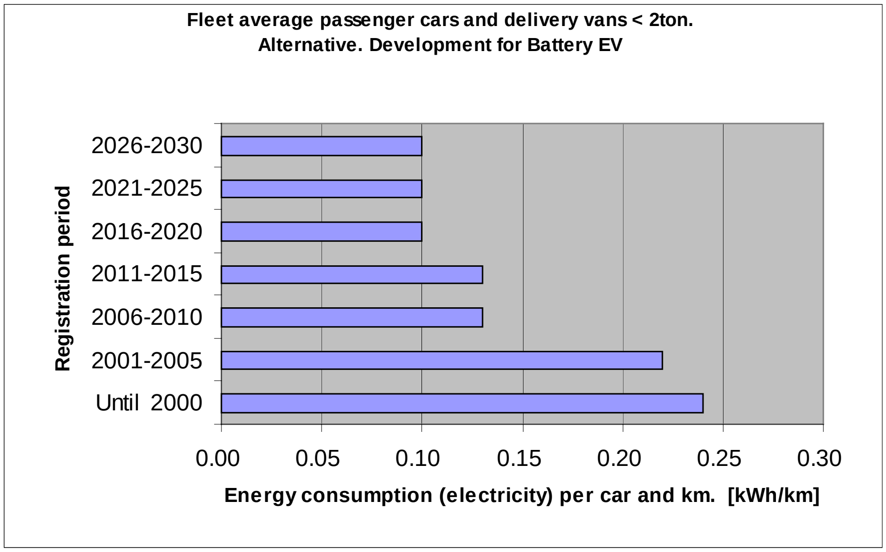

Figure 4-2 Specific energy consumption assumed for future battery electric vehicles (BEV). Passenger cars and delivery vans <2 tons. . Data based on [16]. Units: kWh_{el}/km.

When comparing the average ICEV and BEV energy efficiencies shown on Figure 4-1 and Figure 4-2, it must be noticed, of course, that the different energy qualities, gasoline and electricity, are being compared. However, the future level for energy efficiency of 0.10 kWh_{el}/km, assumed for the BEV beyond year 2015, is very low in energy resource terms compared to the reference development. The reference assumes an ICEV gasoline efficiency of 0.55 $kWh_{gasoline}$/km beyond year 2010.

Even compared to the very energy efficient ICE vehicle mentioned, 33km/litre gasoline or 0.277 $kWh_{gasoline}$/km, the future BEV must be considered superior in energy resource (and exergy) terms. (E.g. to generate and deliver 0.1 kWh_{el} based on fossil fuel requires about 0.2 $kWh_{gasoline,\ diesel\ or\ natural\ gas}$ at high energy efficient CC plants today, and less may be required based on future technology.)

Electricity based transport solutions and the BEV are in particular interesting seen from both the point of view of CO_2 reduction and the future energy resources available. Relative to the most important renewable energy resources (wind power, photovoltaic and hydropower) it can be noticed that these resources are harvested in form of electricity. To integrate these resources to cover energy needs for road transport is very attractive, due to the straight and rather simple BEV energy chain from resource to wheel, and due to the high energy efficiency potential of this chain.

4.1.3 Direct hydrogen fuel cell vehicle (HFCV)

A future direct hydrogen fuel cell vehicle (HFCV) may offer zero emission, low noise, energy efficiency superior to the ICE, long range and fast refill. A number of large car manufacturers have developed and demonstrated the HFCV vehicles in prototypes. The HFCV is expected to offer transport services fully comparable to the conventional ICEV.

The type of fuel cell considered for road transport applications is predominantly the PEM fuel cell. However, other fuel cells and systems, which may involve energy carriers other than hydrogen, are also considered (e.g. the zinc/air fuel cell [19] and SOFC).

Hydrogen is required for the PEM fuel cell operation. But due to uncertainty associated with the building up of an infrastructure for hydrogen production and distribution, and to some extent uncertainty concerning developing the appropriate on board hydrogen storage systems (offering safety, low weight, low volume and low cost), other and more conventional energy carriers are also considered. Gasoline and methanol are among the other energy carriers considered to introduce the fuel cell vehicles on the market. However, these require on board reformers to convert e.g. methanol to hydrogen. Such reformer systems have been and are being developed.

Reformer based fuel cell vehicles may yield an early market integration of fuel cell technology for transportation, if the appropriate liquid fuels are easily integrated in the present infrastructure, or if the existing fuels may be used. However, the on-board conversion e.g. from clean gasoline to hydrogen via reformers does not inherit the attractive on-road zero emission characteristics offered by the direct hydrogen vehicles. Furthermore, stationary larger-scale reformers may be expected to offer better energy efficiency than the small-scale mobile units operated in vehicles at low load factors. A link to liquid fuels may involve reduced overall energy efficiency and may furthermore limit the potential energy resource flexibility and the potential CO_2 emission reduction benefits compared to the direct hydrogen energy paths.

Considering the fuel supply infrastructure and vehicle costs as a whole, there are studies that indicate, e.g. ref.[18], that the direct hydrogen energy paths for fuel cell vehicles can be attractive economically relative to corresponding paths, which involve clean gasoline or methanol as energy carriers, and reformers on-board the individual vehicles.

Generally the HFCV is expected to enter the market before year 2005. As an example it can be mentioned, that DaimlerChrysler has announced to offer sale of hydrogen fuel cell busses by the end of year 2002. Vehicles, such as busses in regular service, can return to a central hydrogen filling station, and for such transport segments the initial hydrogen infrastructure costs are favourable. Introduction of the HFCV in such niches is important for the initiation of an hydrogen supply infrastructure covering larger regions.

In this scenario analysis focus is put on the direct hydrogen fuel cell vehicle that requires a hydrogen supply and refuelling infrastructure and an on-board storage system for hydrogen. The on-board hydrogen storage can be e.g. gaseous hydrogen in pressure vessels, a solid hydride type of storage etc.

Furthermore, in the scenarios it will be assumed that the hydrogen supply system is based on electricity and electrolysis. Hydrogen production based on natural gas via steam methane reformers is an interesting option, but the following scenarios put focus on the energy path, where grid electricity and electrolyses are elements in a hydrogen infrastructure. Hydrogen production via electricity allows the diversity of energy resources in the electricity supply to enter the supply. Grid connected electrolysers are in the scenario analysis assumed to constitute the main hydrogen supply infrastructure. Detailed analyses on such hydrogen supply systems and infrastructures compared to alternatives and compared to the present gasoline supply infrastructure are found in e.g. [5], [8], [9], [12], [15],[18].

Figure 4-3 shows the assumed development of the on-board hydrogen consumption of the HFCV, for the considered transport segment, passenger cars and smaller delivery vans.

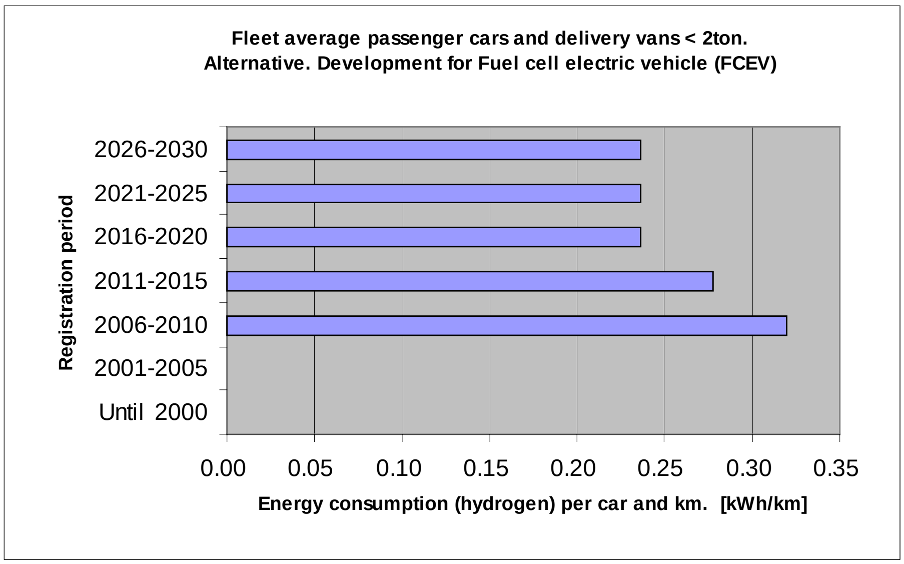

Figure 4-3 Specific energy consumption assumed for future direct hydrogen fuel cell vehicles (HFCV). Passenger cars and delivery vans <2 tons. Data based on [6]. Units: kWh_{el}/km.

The HFCV marketed in the period 2006-2010 is assumed to have a specific energy consumption of about 0.32 $kWh_{hydrogen}$/km, and beyond year 2015 the hydrogen consumption of the HFCV is expected to have declined to a level of about 0.24 $kWh_{hydrogen}$/km. (To convert to hydrogen volumes use the HHV of 3.55 kWh/Nm3.)

Comparing the defined average ICEV vehicle on gasoline (Figure 4-1) and the HFCV vehicle on hydrogen it is seen that in energy terms the HFCV is expected to require about half the energy input of the ICEV per vehicle km. The average ICEV energy efficiency beyond year 2010 is estimated to 0.55 $kWh_{gasoline}$/km in the reference situation.

Compared to a very energy efficient future ICE vehicle, able of 33km/litre gasoline or 0.277 $kWh_{gasoline}$/km, the future HFCV able of 0.24 $kWh_{hydrogen}$/km may not be considered superior in energy resource (and exergy) terms, but at about the same level.

4.2 CO_2 emission for BEV, FCEV and ICE vehicles. The Danish case.

The ICEV specific CO_2 emission per km. travelled is determined from the combustion and energy efficiency of the vehicle, and the type of fuel used. Technical developments assumed during the analysed period change the energy efficiency of new vehicles entering the fleet. The fossil fuels used, however, are the same or assumed unchanged. Thus, only in-vehicle technical developments influence the specific CO_2 emission per km for the new ICEV.

For the new BEV entering the transport fleet both the vehicle technical developments and the power supply system developments influence the specific CO_2 emission of the vehicle. And the CO_2 characteristics of the individual vehicle change over time according to changes in the power supply charging the vehicle.

For the individual HFCV, when hydrogen is produced via electrolysis based on electricity from the grid, the specific CO_2 emission per vehicle and km likewise will depend both on the electricity supply system development and the new vehicle technical development.

4.2.1 CO_2 emissions from the Danish electricity sector

An increasing fraction of the Danish electricity production is cogenerated as combined heat and power production (CHP). In 1997 50% of the Danish electricity consumption was CHP based. According to Energy21, The Plan scenario, the CHP fraction of the electricity (and heat) production will increase further, and improve the overall system energy efficiency.

CHP and CO_2 emission. The method applied.

To assign CO_2 emission per kWh of electricity generated from a combined heat and power production plant, the fuel consumption at the CHP plant must be split in two. One part of the fuel consumption is assigned the power production, and the rest is assigned to the heat production.

There is not a single solution to how this split should be done. However, often this split is done based on whether the two products, electricity and heat, are products of equal value or whether one product is considered the primary.

In cases where the primary function of the CHP plant is electricity production, and the heat produced thus is the secondary product, the so-called Cv-method is often applied. In cases where the heat and power are considered as equal important products, the so-called Cm-method is often applied.

Both these methods are applied in the analysis. The following guidelines have been used to determine the primary product for individual CHP-plants:

- Cv-method.
  For larger CHP plants of capacity > 25MW the Cv-method is used.
  (Applied for the larger extraction plants. Often this method is also termed 'the condensing plant method'.)
  Fuel assigned the power production=
  (Total fuel consumption)/(1+Cv(Prod.Heat)/(Prod.El.))*

- Cm-method.
  For smaller CHP plants of capacity <= 25MW the Cm-method is used.
  (Applied for smaller backpressure units. Often this method is also termed 'the proportionality method'.)
  *Fuel assigned the power production = (Total fuel consumption)*Cm/(Cm+1)*

For the individual CHP-plants in Energy21, The Plan scenario, the above rule is used to define primary product of the plant. The CO_2-emission per kWh assigned to electricity production from the plant is then determined according to either the Cm-method or the Cv-method for the fuel split.

CO_2 emission development

In the Danish situation the CO_2 characteristics of the electricity system have changed considerably towards lower specific CO_2 emission during the past decades.

To a large extent the Danish electricity supply system is based on coal. However, since the early 1970's coal consumption has decreased to about the half. The main changes in the Danish electricity supply system include the facing out of coal and oil based electricity production, substitution towards natural gas, increased CHP production and increased utilisation of renewable energy, in particular wind power and biomass based CHP.

An ambitious and persistent energy and environmental policy, a broad energy planning process and national RD&D programmes, subsidy schemes etc. are important elements in this system development. This transformation process in the Danish energy system is ongoing, towards increasing the overall system energy efficiency and towards utilisation of renewable energy, to achieve CO_2 reduction.

This development is reflected in Figure 4-4. Until year 1997 numbers on the figure show historic data on the CO_2 emissions per kWh electricity delivered from the grid. Numbers shown onwards, for year 2005 and year 2030, are calculated (using the BRUS-model) based on the system configuration in detail for the power (and CHP) supply according to the development path, termed The Plan scenario, in the national energy plan, Energy21 [2].

In the past ten year period in particular the decline has been pronounced. Year 1997 the specific CO_2 emission for electricity consumed in Denmark was 706 gCO_2/kWh. Relative to the year 1980 level of 1022 gCO_2/kWh a reduction of well 30% has been observed until year 1997.

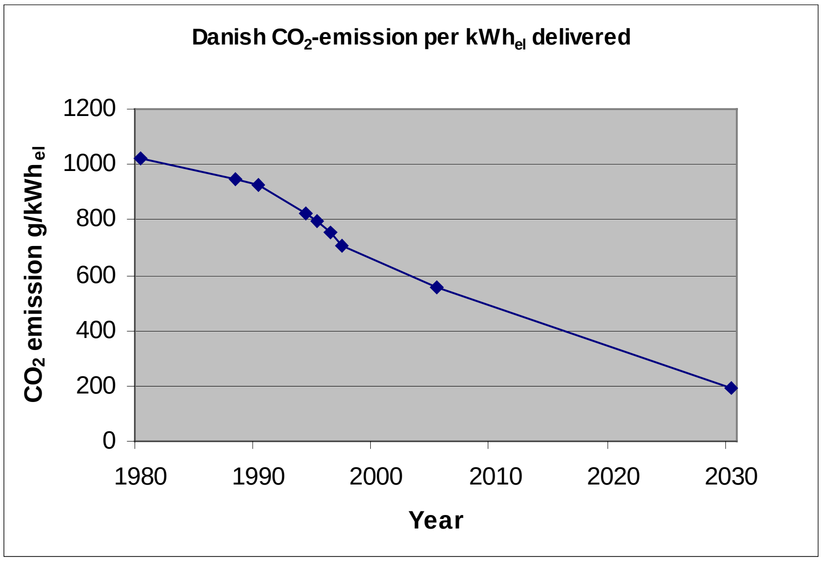

Figure 4-4 CO_2 emission per kWh of electricity delivered at the consumer. Statistics until 1997 from: The Danish Energy Agency. Forecast data beyond year 1997: Based on the Danish energy plan, Energy21, The Plan scenario [2].

According to the Danish energy plan the decline will continue. Calculations based on the expected medium-term system development show, according to Energy21, The Plan scenario, that the specific CO_2 emission for electricity year 2005 has reduced to 556 gCO_2/kWh. Further calculations according to The Plan scenario for the long-term development, year 2030, show, that the specific emission is expected to reduce to 192 gCO_2/kWh. Relative to the 1980 level, a more than 80% reduction in the specific CO_2 emission per kWh electricity is expected for year 2030.

In short, the main supply changes in the power system, up to year 2030, are the phasing out of coal for electricity production, a continued substitution towards natural gas and biomass in CHP production and large-scale integration of wind power. Almost half of the electricity production year 2030 is based on wind power. The Plan scenario, year 2030, includes 1,500 MW on land and 4,000 MW offshore wind capacity.

To determine emission of CO_2 from the BEV and HFCV the electricity supply system development during the lifetime of the vehicle must be considered.

4.2.2 ICEV CO_2-emission development. Reference

The specific CO_2 emission per km travelled in the ICEV is determined from the vehicle energy efficiency and the type of fuel used. As the type of fuel has been assumed fixed only technical developments in energy efficiency of the defined average vehicle may improve the specific emission. Figure 4-5 defines the reference development for new internal combustion engine vehicle entering the fleet. This defined average ICEV in the Danish road transport may later also be referred to as the conventional car.

For the conventional ICEV in the present Danish fleet the average specific CO_2 emission has been calculated to 176 gCO_2/km, as illustrated in Figure 4-5. New cars entering the fleet in the period 2006-2010 are expected on average to have specific CO_2 emission close to 150 gCO_2/km. And future new cars entering the fleet are expected on average to have specific CO_2 emission slightly below this level.

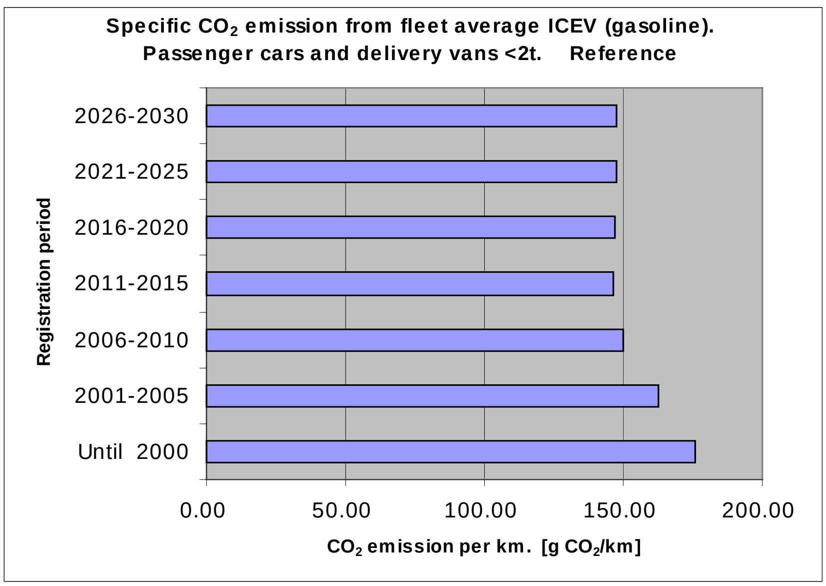

Figure 4-5 Specific CO_2-emission for passenger cars and delivery vans <2 tons. Based on forecasts of Danish transport work and fleet development from The Road Directorate, Ministry of Transport, Denmark.

The fuel mix for the future ICEV fleet has been assumed to be 90% gasoline (on energy basis) and 10% diesel. This is close to the present fuel mix for this category of vehicles in Denmark, i.e. passenger cars and delivery vans of weight less than 2 tons.

The Figure 4-5 reference development described for the Danish ICEV fleet is close to being consistent with the voluntary agreement (1998) between the car industry and the EU to aim to reduce the CO_2 emission to 140 gCO_2/km for the average new car in the EU by year 2008. The 140 gCO_2/km aim corresponds to an energy consumption of 0.533 $kWh_{gasoline}$/km (or 0.525 kWh_{diesel}/km) and 17.1km/litre gasoline (or 19.0 km/litre diesel).

The reference development here described declines to a level of about 0.55 kWh/km during the same period, where the fleet fuel mix assumed is 90% gasoline and 10% diesel.

A so called '3litre vehicle', able of travelling 33km/litre of gasoline, corresponding to a specific energy consumption of 0.27 $kWh_{gasoline}$/km, will have a specific CO_2 emission of 72 gCO_2/km. Thus, a '3litre vehicle' emits about half the CO_2 emission expected of the future fleet average car as seen from Figure 4-5.

4.2.3 BEV CO_2 emission development

The CO_2 emission performance of the battery electric vehicle, off course, is linked to the CO_2 performance of the electricity system supplying the BEV. Thus the particular BEV change emission characteristics according to where and when it is deployed or charged.

The BEV has potential to offer zero CO_2 emission. If battery recharge is based on electricity generated from e.g. renewables or nuclear power virtually no CO_2 emission is associated with using the vehicle. Likewise, if the BEV owner chooses to purchase green electricity only, or if the BEV may be situated e.g. in Norway, where hydropower presently covers about 99% of the supply, the BEV operation is virtually CO_2 neutral.

Within a given year the Danish power system operation may vary considerably, and thus correspondingly the physically related specific CO_2 emission per kWh produced. This may be due to CHP related variations, day/night and summer/winter, in the system operation, and it may be due to seasonal and annual variations in wind power generation etc. It has been assumed here, however, that the CO_2 emission per kWh of electricity consumed from the grid by electric vehicles corresponds to the annual average CO_2 emission from the total electricity supply system.

The specific CO_2 emission development for the battery electric vehicle in the future Danish road transport fleet has been calculated for two cases or paths for the electricity generating system development during the period.

In the first case, the CO_2 emission characteristics are fixed. The year 1997 electricity supply system attributes are assumed maintained throughout the period, i.e. to year 2030. This reflects CO_2 emission consequences, due to the BEV technical development only, during the period.

In the second case the electricity supply system development expected according to Energy21, The Plan scenario, is assumed, as described in section 4.2.1. This case will reflect the combined effect of the BEV technical development and the power supply system development.

EV CO_2 emission development - assuming fixed electricity supply system (Danish 1997 electricity system assumed)

In Figure 4-6 it has been assumed that the electricity supply system is unchanged during the period analysed. Throughout the period electricity is assumed generated as from the Danish 1997 electricity supply system. An annual average CO_2 emission of 706 gCO_2 per kWh delivered at the consumer characterises this system.

Figure 4-6 thus reflects the specific CO_2 emission development associated with operating new battery electric vehicle entering the fleet along the period, when the vehicle technical development is considered only.

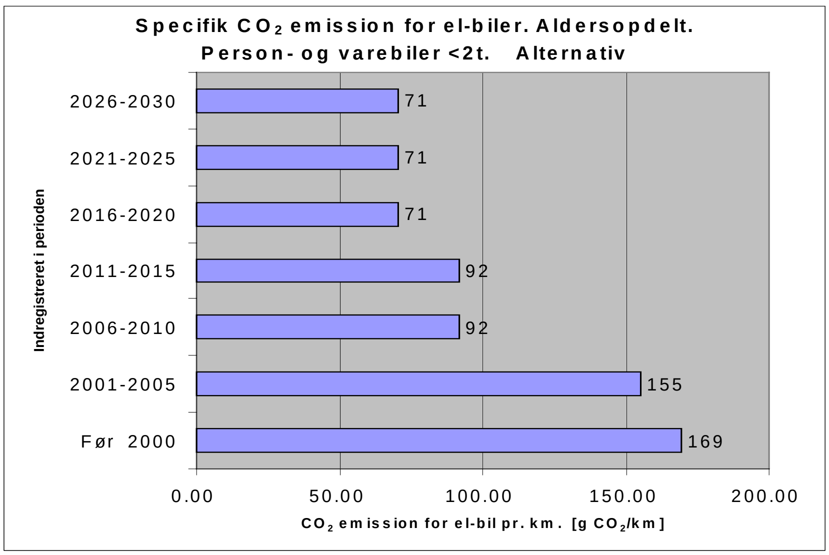

Figure 4-6 Specific CO_2 emissions from battery electric vehicles (BEV). Assumed: Fixed 1997 level electricity supply system CO_2 emission per kWh.

Figure 4-6 shows that the technical development of the BEV is expected to reduce the CO_2 emission per km driven from the 1997 level of 169 gCO_2/km down to a level of 71 gCO_2/km for the future BEV entering the fleet after year 2015.

The rapid technical development expected for the BEV, increasing energy efficiency substantially, will improve the CO_2 performance of the BEV relative to the ICEV. Even with the present assumption (of a static 1997 level electricity supply system) the future BEV may become much superior to the reference ICEV. The technical improvements expected for the BEV concern most of the components specific for BEV drive train [16]. Contrary to the ICEV the BEV technology has not yet fully matured. Comparing Figure 4-6 and Figure 4-5 it is seen, that the BEV CO_2 emission per km is expected to reduce to less than half of the ICEV in about 10-15 years, due only to the BEV technical development assumed.

Comparing today's ICEV (that emits in average176 gCO_2/km) and a corresponding BEV of today in the Danish system (that emits 169 gCO_2/km) it appears that only a minor CO_2 benefit can be expected. The main environmental benefits gained from the EV today are health benefits related to reduction of air pollution from the ICEV road traffic, particularly in the densely populated and urban areas. However, the CO_2 reduction benefit of the average EV sold today will depend on the future development of electricity supply, as described in Figure 4-4. In the Danish case the CO_2 benefit will increasingly build up during the BEV lifetime.

BEV CO_2 emission development – including developments in the electricity generation system (Danish Energy21 Plan scenario assumed)

Electricity supply systems in general have limited short-term fuel flexibility. The long-term flexibility, however, is considerable e.g. relative to the energy resources available. Via the BEV this long-term flexibility is transferred to the transport sector. The BEV can become an important link, enabling the transport sector to gradually increase utilising e.g. the renewable energy resources, such as wind power and photo-voltaic.

Such development is illustrated for the Danish situation, where the Energy21, The Plan scenario [2], describes an electricity system development towards diverse and large-scale utilisation of renewable energy resources.

Taking into account the expected development of the Danish electricity supply system the BEV CO_2 characteristics change considerably as seen in Figure 4-7.

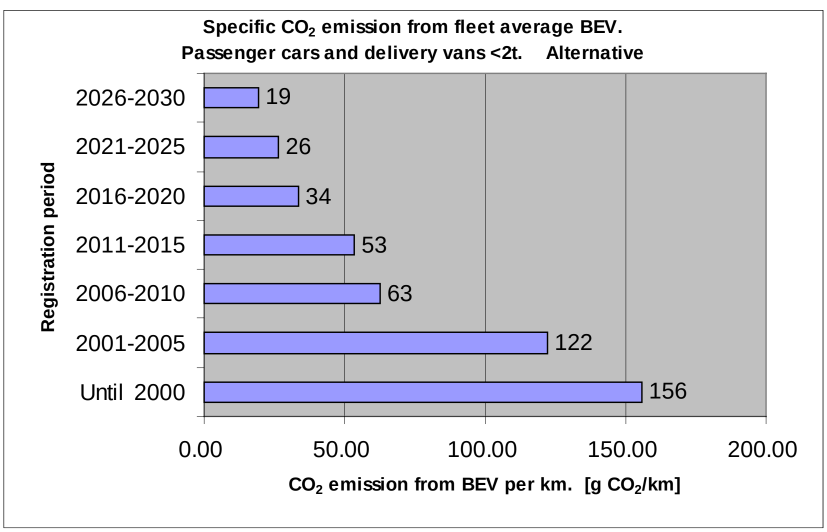

Figure 4-7 Specific CO_2 emissions from battery electric vehicles (BEV). Assumed: Danish electricity supply system development according to Energy21, The Plan scenario [2].

Comparing Figure 4-7, where the Energy21 electricity supply system development has been included, to Figure 4-6, where the 1997 system CO_2 intensity has been assumed, a further reduced specific CO_2 emission per km is seen for the new BEV. A further reduction of about a factor of three may be expected beyond year 2015, when the BEV electricity supply system develops according to The Plan scenario in Energy21.

Compared to the defined average ICEV development described in Figure 4-5, the comparable BEVs in the Danish system described in Figure 4-7 have significant lower CO_2 emission. The year 2030 state of development of the BEV and the electricity supply system result in a BEV specific CO_2 emission per km less than 15% of the corresponding gasoline based ICEV.

The BEV may be particularly suited for utilising a fluctuating electricity production. The grid connected battery electric vehicle represents a flexible load, where the time of recharge to a large extent may be postponed and intermittent in correspondence with the power supply. If such load management flexibility or power regulation capabilities in the BEV stock can be utilised to facilitate further the integration of e.g. wind power production in the electricity system, the BEV CO_2 emission may reduce even more.

4.2.4 HFCV CO_2 emission development

It has been assumed that hydrogen to supply the direct hydrogen fuel cell vehicles is produced via electrolysis, and electricity from the grid. It is furthermore generally assumed in the analysis, that the conversion efficiency in the hydrogen supply from grid electricity to hydrogen stored onboard the vehicle is 85%.

Throughout the period an efficiency of 90% has been assumed for electrolytic hydrogen production. Compression and transmission (if required) are assumed to increase electricity consumption for the hydrogen production about 5% [14]. This may be a somewhat conservative assumption to maintain throughout the period analysed. However, such fixed assumption can be convenient for interpreting results.

Apart from electrolytic production of hydrogen for the direct hydrogen fuel cell vehicle HFCV, numerous hydrogen production processes and energy resources may contribute to the hydrogen supply. As for the BEV a high long-term fuel flexibility is transferred to the HFCV, via the electrolytic hydrogen production and the link to the power supply system. But in addition hydrogen from various sources and processes contribute to the HFCV flexibility. And as for the BEV the HFCV has potential to offer clean and CO_2 neutral road transportation.

The development of the direct hydrogen fuel cell vehicle CO_2 characteristics are shown in Figure 4-8. The figure describes the specific CO_2 emission development of new HFCV vehicles entering the fleet in the period analysed, when both the expected technical development of the vehicle and the expected development of the Danish electricity supply system have been taken into account.

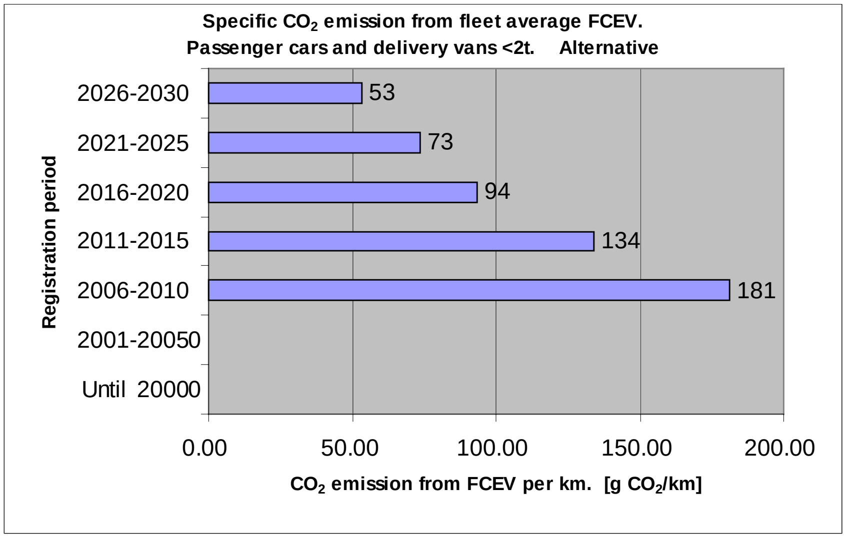

Figure 4-8 Specific CO_2 emissions from direct hydrogen fuel cell vehicles (HFCV). Assumed: Danish electricity supply system development according to Energy21, The Plan scenario [2].

Based on the assumptions, the HFCV of beyond year 2010 is expected to have a lower specific CO_2 emission than the defined reference ICEV. Whereas the CO_2-emission of the ICEV is assumed to be close to 150 gCO_2/km from beyond year 2005, the emission from the new HFCV declines throughout the period. Year 2025/2030 the HFCV emission is expected to have declined to about 53 gCO_2/km. Further technical development of the HFCV and the power system development towards reduced CO_2 emission make the HFCV superior to the ICEV from the CO_2 emission point of view.

The '3litre' ICEV, that emits 72 gCO_2/km, has CO_2 emission comparable to a HFCV of vintage beyond year 2020, when the hydrogen supplied is produced via electrolyses fed from the Danish electric grid, as seen from the figure.

Compared to the battery electric vehicle, charging from the Danish power supply system developing according to Energy21, The Plan scenario, the HFCV specific CO_2 emission is about twofold the BEV emission throughout the period analysed, as seen from Figure 4-8 and Figure 4-7. This reflects the less efficient energy path of the electrolytic based HFCV compared to the BEV.

As for the BEV, the HFCV may be particularly suited for utilising a fluctuating electricity production, such as wind power. Stationary electrolytic hydrogen production plants may be able to postpone production towards time periods that are favourable for the power supply. This load management potential, off course, depends on the chosen capacity factor for electrolyser facilities, the hydrogen storage capacity and daily sales etc.

4.3 Summary on specific energy consumption and CO_2 emission

For the defined Danish fleet average vehicle in the transport segment, passenger cars and smaller delivery vans, the assumed development of the specific energy consumption and CO_2 emission for new ICEV, BEV and HFCV are summed up in Table 4-1.

For the BEV and HFCV the local emissions to the air of pollutants are virtually zero. Here, only the CO_2 emission in the overall energy system is considered.

The BEV and HFCV energy supplies are based on electricity from the Danish grid. It has been assumed that hydrogen to operate the direct hydrogen fuel cell vehicle is produced via electrolysis with an overall conversion efficient on energy basis, from grid electricity to hydrogen stored onboard the vehicle, is 85% generally.

From Table 4-1 it is seen that for the ICEV only a moderate reduction in the specific consumption of gasoline per km driven in the fleet average vehicle is expected [4] during the period. The defined fleet average vehicle is seen to require about twofold the fuel of the so-called '3litre' ICEV (33km/litre) vehicle. Likewise, for the emission of CO_2.

It shall be noticed, that the energy efficiencies of the ICEV, BEV and HFCV shown in Table 4-1 involve the different energy carriers electricity, hydrogen, and gasoline. Comparing these energy efficiencies, therefore, is not direct.

Table 4-1. Vehicle energy efficiency and specific CO_2 emission. Comparison for defined average fleet vehicle of type ICE, BEV, and HFCV. Power supply according to Energy21, The Plan scenario.

Type of vehicle Size: Average fleet	1997/2000	2005/2010	2025/2030
ICEV Reference			
$kWh_{gasoline}/km$	0.66	0.55	0.55
gCO_2/km	176	150	150
ICEV '3litre aim'			
$kWh_{gasoline}/km$	-	0.27	0.27
gCO_2/km	-	72	72
BEV			
$kWh_{electricity}/km$	0.24	0.13	0.10
gCO_2/km	156	63	19
HFCV			
$kWh_{hydrogen}/km$	-	0.32	0.24
gCO_2/km	-	181	53

Comparing the BEV and HFCV it is seen that using the HFCV the expected CO_2 emission is more than twofold the expected emission from the comparable size BEV.

This reflects the potentially very efficient energy path, from electricity to wheel, of the BEV.

Compared to the conventional ICEV, the battery electric vehicle (BEV) is very attractive from both an energy efficiency and CO_2 emission point of view. The CO_2 emission may have dropped to almost 1/3 of the expected average ICEV for new BEVs entering the fleet in the period 2005 to 2010. This is less the CO_2 emission of the ‘3litre’ vehicle.

BEVs entering the fleet in the period 2025 to 2030 have considerable lower CO_2 emission than the ICEV. Furthermore, the BEV vehicles, that have entered the fleet, will improve their CO_2 characteristics over time, due to the power supply system development towards lower specific CO_2 emission per kWh delivered.

The HFCV, that matches the ICEV in fast refill and range per refill, will not from a CO_2 reduction point of view match the ICEV before 2010, when the hydrogen is produced via electrolysis in the Danish system. The HFCV though is very attractive relative to reducing road traffic air pollution. If hydrogen is produced from e.g. methanol or gasoline, the reformer based HFCV can have low CO_2 emission compared to the average ICEV. Seen from both the emission and energy resource perspective, the development of the HFCV is very positive relative to the ICEV.

This analysis focuses on the grid electricity based direct hydrogen fuel cell vehicle, only. Hydrogen is tanked and stored onboard the vehicle. Such HFCV has energy flexibility inherited from the power supply, and may furthermore tank hydrogen from numerous hydrogen production options. The HFCV technology may offer clean and CO_2 neutral transport able to match the service and comfort of the ICEV.

Based on the assumptions, the HFCV becomes CO_2-attractive relative to ICEV beyond year 2010. HFCVs entering the fleet in the period 2025 to 2030 have considerable lower CO_2 emission than the average ICEV. This difference is about 1:3 as seen from Table 4-1.

The technical developments described for the defined average fleet vehicle form inputs to the scenario analyses described in chapter 5 below.

5 Scenarios for Danish road transport

The overall aim of the scenario analysis is to look into the long-term possibilities for reduction of

- air pollution from road transport and
- CO_2-emisson from road transport,

via large-scale integration of the alternative vehicles, battery electric vehicles (BEV) and direct hydrogen fuel cell vehicles (FCEV) in the Danish transport sector. Such vehicles have already emerged on the market or are expected to come on market in the near future.

No local air pollution is associated with the BEV and FCEV operation. If electricity and hydrogen used in the vehicles are generated from non-fossil energy sources, these vehicles may furthermore offer zero CO_2-emission during operation.

The aim of the scenario analysis is to estimate the long-term consequences, if a large-scale effort is carried out to substitute the conventional internal combustion engine vehicle (ICEV) with such alternative vehicles.

The analysis will concentrate on such substitution options in the Danish transport segments, that cover passenger cars and delivery vans of weight less than 2 tons.

The consequences focussed on in the scenario analysis are the potential:

- Energy substitution effects, and
- CO_2 emission reduction achievable.

Furthermore it is an aim to estimate the time scales involved for such effort to have effect. The electricity demand increase, to operate the electricity based road transport fleet in the scenarios, is compared to the Danish wind power production.

Basic assumptions

Electricity from the Danish power supply system is assumed to form basis for both the BEV and HFCV operation. Hydrogen to operate the HFCV is assumed generated via electrolysis. The Danish power supply system is assumed to develop according to the Danish energy plan, Energy21, The Plan scenario, during the period analysed, up to year 2030. Thus the transport alternatives focussed on concern a transition towards electricity based road transport options.

The expected technical development of the alternative vehicles, and associated market potentials and assumed market penetration potentials, as well as the expected replacement rate in the Danish transport fleet, form the basis of the analysis.

The basic assumptions concerning the technical development of the defined average fleet conventional ICEV and for the comparable size alternative BEV and HFCV are described in chapter 4 above.

Scenarios

Three scenarios are set up. The scenarios cover the period up to year 2030, and reflect technical options expected for the integration of battery electric vehicles and the direct hydrogen fuel cell vehicles.

All scenarios illustrate a large-scale substitution away from the conventional vehicle based on fossil fuel, and towards the electricity based alternative vehicles. The expected time scales involved for such transition are illustrated. As mentioned above, the overall aim in each of the scenarios is to reduce emission of pollutants and CO_2 from road transport.

The scenarios designated S1, S2, and S3 are set up as follows:

S1: BEV scenario.
Aims to integrate most energy efficient technology and to achieve maximum fossil fuel substitution and CO_2 emission reduction per vehicle.
Being the most energy efficient among the technologies considered the battery electric vehicle technology is promoted for rapid transport fleet integration.
Limited range of the BEV limits the market potential. Year 2030 about 40% of the fleet or about 1 million vehicles are aimed to become BEVs in the scenario.

S2: HFCV scenario.
Aims to integrate energy efficient technology, with range per refill fully comparable to the conventional ICEV, to achieve fossil fuel substitution and CO_2 emission reduction.
The direct hydrogen fuel cell vehicle technology compared to the ICEV is expected to offer energy efficiency and CO_2 emission gains beyond year 2010, and from then of the vehicle is promoted for rapid transport fleet integration.
Infrastructure build up for hydrogen production and tanking is needed. Year 2030 about 40% of the fleet or about 1 million vehicles are aimed to become HFCV in the scenario.

S3: Combined BEV & HFCV scenario.

Aims to minimise CO_2 emission and consumption of fossil fuels in the road transport sector via promoting high market penetration of the electricity based alternative vehicles.

The scenario aims to half CO_2 emission by year 2030 relative to the baseline development for the road transport segment considered.

The S3 scenario is the composition of the S1 and S2 scenarios. Year 2030 about 80% of the fleet or about 2 million vehicles are aimed to become electricity-based vehicles, BEV or HFCV.

All scenarios include the long-term forecast from The Danish Road Directorate, Ministry of Transport [4], as the reference development for the Danish transport fleet.

It is assumed that the vehicle cost for the consumer at the time of their introduction in the scenarios is not prohibitive for a large-scale application. A persistent and forward-looking policy to support the integration of these new vehicles is implicitly assumed.

5.1 The Danish transport sector. Energy consumption and CO_2 emission

The forecast [4] from the Danish Road Directorate, Ministry of Transport, for the development of the Danish transport sector, up to year 2030, forms a reference or the baseline development for the scenario analysis.

The scenarios comply with this expected development in transport service needs, the size of the fleet, energy consumption and CO_2 emission. In the scenarios focus is put on the road transport sub-sector, that covers passenger cars and delivery vans of weight less than 2 tons.

For this sub-sector an average vehicle for each vintage group is defined for the scenario analysis. The defined vehicle is characterised by the specific fuel consumption, fuel mix, and the annual driving distance, representing the Danish fleet averages in the transport segment considered. This defined average ICEV and its expected development for new cars entering the fleet is derived from forecast results in [4].

According to [4] the expected development for the energy consumption and CO_2 emission in the overall transport sector is described in sections 5.1.1 and 5.1.2 below.

5.1.1 Transport energy consumption. Forecast baseline development

The energy consumption forecast is shown in Figure 5-1 for the Danish transport sector in total. Until year 1997 the statistical data are shown.

The sub-sector, passenger cars and delivery vans < 2 tons, considered in the scenario analysis is shown at the bottom of the figure. Generally, throughout the period this sub-sector is expected to consume about half the total transport energy consumption. More than 99% of the consumption is expected to be oil products.

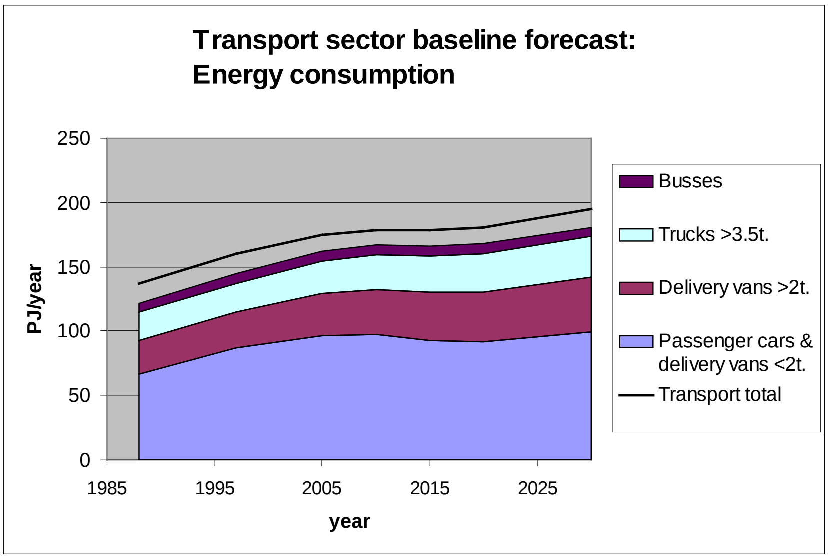

Figure 5-1 Baseline forecast of energy consumption in the Danish transport sector. Consumption related to road transport is shown split on the segments busses, trucks, delivery vans>2 tons and passenger cars and delivery vans <2 tons. Source: [4] The Danish Road Directorate.

Corresponding to this energy consumption the baseline CO_2 emission is shown in Figure 5-2 below.

5.1.2 CO_2 emission from transport. Forecast baseline development

From Figure 5-2 it is seen that throughout the period the sub-sector considered, passenger cars and delivery vans < 2 tons, is expected to emit about half of the total transport sector CO_2 emission. This reflects that the consumed fuel mix during the period is expected to be almost unchanged in the baseline.

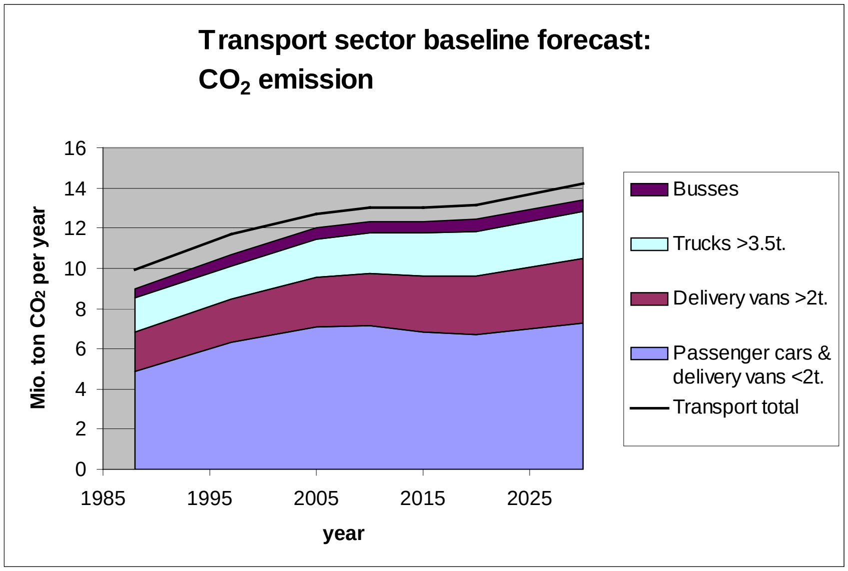

Figure 5-2 Baseline forecast of CO_2 emission from the Danish transport sector. Emission related to road transport is shown split on the segments busses, trucks, delivery vans>2 tons and passenger cars and delivery vans <2 tons. Source: [4] The Danish Road Directorate.

The total CO_2 emission, expected year 2030, is 14.2 million tons CO_2 per year. Relative to the 1988 emission this is an increase of about 43% during the period.

Year 2030 the baseline emission from sub-sector, passenger cars and delivery vans <2 tons, is estimated to 7.28 million tons CO_2 per year. Relative to 1988 this is a 49% increase. In the S3 scenario the aim set up is to reduce CO_2 emission for this sub-sector to the half by the end of the period, from introducing electricity based vehicles only. The scenario S3 reduction aim is 3.6 million tons CO_2 per year.

Danish CO_2 policy targets for the transport sector

The Danish Action Plan for the Transport sector development [7] sets up the national target to reduce CO_2 emission by year 2005 to the 1988 level of emission. A long-term target for year 2030 is furthermore set up. This long-term aim for the transport sector is to reduce CO_2 emission by 25% relative to the 1988 level.

As seen from Figure 5-2 the policy aim to stabilise and subsequently reduce the transport sector CO_2 emission is not meet by the forecast development described. Furthermore, a subsequent assessment from the Danish Ministry of Transport of the transport sector development indicates, that the CO_2 emission to be expected from transport year 2005 may be about 16% above the target of the year 1988 level, if no further actions are carried out.

5.1.3 CO_2-emission developments according to Energy21

For comparison, the CO_2 emission developments according to the Energy21, Reference scenario and The Plan scenario, covering the overall Danish energy system are shown in Figure 5-3. Presently, emission from the transport sector amounts to well 20% of the total Danish CO_2-emission.

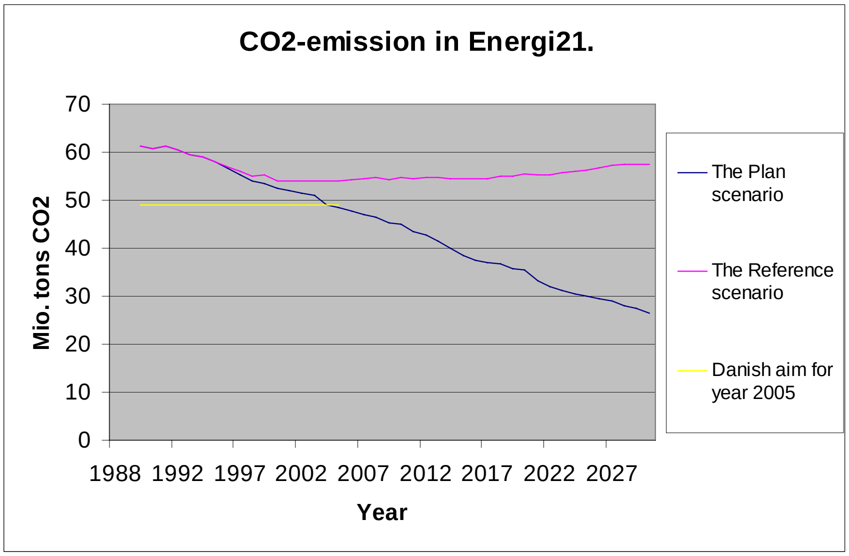

Figure 5-3 Emission of CO_2 according to Energy21, The Plan scenario and The Reference scenario, and the shorter-term national target for CO_2 emission year 2005. Source: Ministry of Energy and Environment (1996).

The development expected according to Energy21, The Plan scenario, for the annual CO_2 emission from the overall energy system shows a steady decrease throughout the period, whereas in the Energy21, The Reference scenario, an almost constant annual CO_2 emission is expected.

A shorter-term national CO_2 reduction target has been set up aiming to achieve a 20% reduction before year 2005. The target implies an upper limit for the overall emission of about 49 million tons CO_2 per year by 2005.

Denmark has expressed its willingness to accept the reduction targets that follow from the conclusions of the International Panel on Climate Change. This would mean a target to reduce the annual CO_2 emission to half the 1990 level by year 2030.

5.2 Market potential assumed for BEV and FCEV in Denmark

Estimated maximal market potentials, based on the technical performance of the BEV and FCEV vehicles, form the starting point for setting up the scenarios. From these potentials, assumptions on the market penetration are superimposed. This is done to reach assumptions on the market shares for new alternative vehicles, among the total number of vehicles entering the fleet in a particular year. The number of new vehicles entering the Danish fleet in total, a particular year, is derived from the forecast assumed for the size of the total fleet [4] and an estimation of the vehicle replacement rate in the Danish fleet, based on statistics.

The future market for BEV and HFCV passenger cars depends on many factors, including the environmental performance, the vehicle investment costs, and operation costs. Essential factors, furthermore, are the range per charge or refill of the vehicles and the infrastructure available for recharge or refill. Such main factors determine which transport segments and where the alternative vehicles may substitute ICEV vehicles.

Future costs of the alternative vehicles are very uncertain and considerations on the potential cost development of the alternative vehicles are not included in this report. Therefore, considerable uncertainty is associated with setting up assumptions for the scenario analyses on the market penetration for alternative vehicles.

Only the technically based potentials, for the BEV and HFCV to substitute conventional ICEVs, are considered in the analysis. The estimation of these potential market shares is based on expected requirements concerning the vehicle range per charge/refill in the present Danish road transport fleet, and data on the expected development for the range per charge offered by the BEV and HFCV.

The BEV range is based on assessments of the battery technology development during the period, and for the HFCV the range per hydrogen refill is based on assessments of the technical development for hydrogen stores on-board the vehicle.

5.2.1 Range and market potential

From analysis of driving patterns in various segments of the Danish road transport sector the relationship shown in Figure 5-4 has been assumed. The figure shows the potential market share for zero-emission alternative vehicles as a function of the potential range per charge/refill.

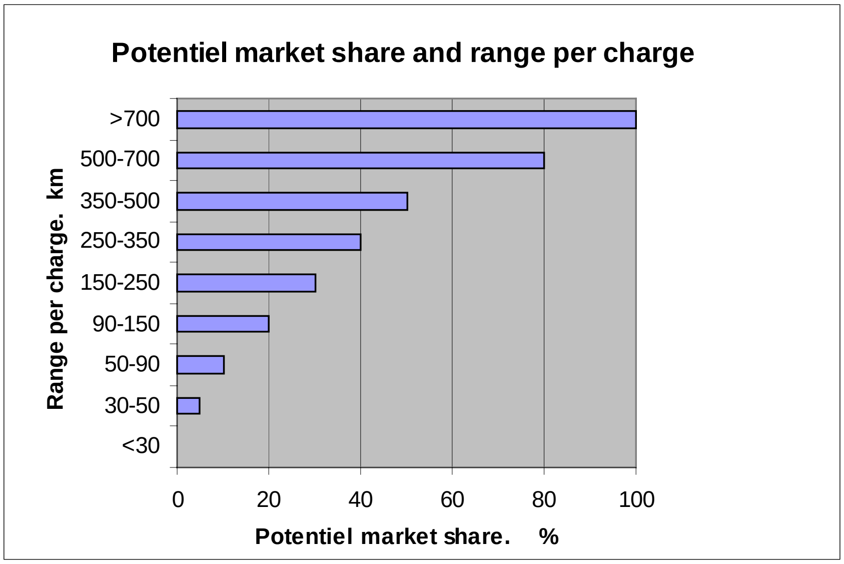

Figure 5-4 Assumption made on the potential market share of a vehicle as function of the range per charge or refill. Transport segment: Passenger cars and delivery vans of weight less than 2 tons.

It is emphasised that these assumptions are uncertain, and that other factors, off course, influence the technical market potential of the BEV.

As seen from Figure 5-4 the potential market share of a vehicle is assumed to reach 100% if the vehicle is capable of a range of more than 700km per charge/refill. A lower range per charge of 90-150km is expected to be associated with a potential market of 20% for new cars, and a range of 250-350km per charge is assumed to be able to cover the needs in 40% of the market.

Throughout the period analysed, the above relation, shown in Figure 5-4, has been assumed as basis for the scenario developments.

5.2.2 BEV market potential

For setting up the scenarios it has been assumed, that the vehicle range per charge determines the future potential market share for the BEV.

BEV range and batteries

The expected development of the ‘affordable’ BEV battery technology is shown in Figure 5-5. For the defined average passenger vehicle in the Danish stock, the development in range per charge is shown, as consequence of the expected battery technology development.

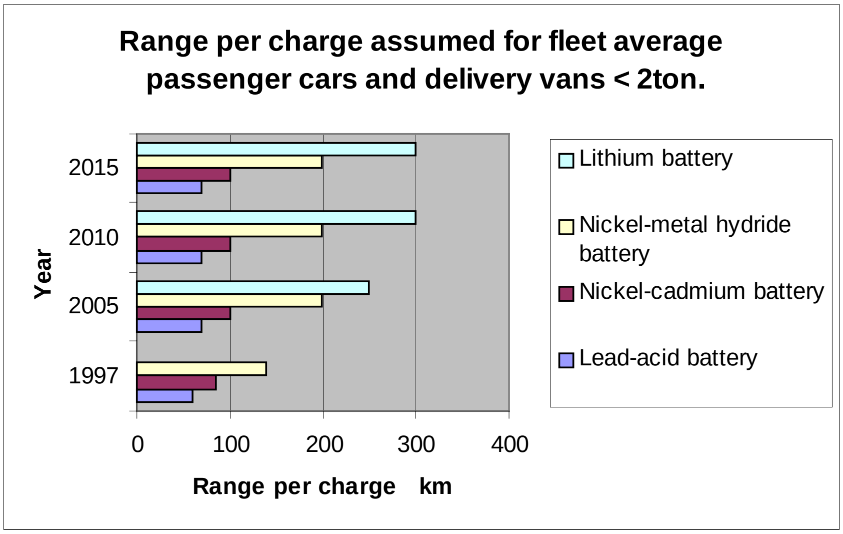

Figure 5-5 Range per charge expected for BEVs as consequence of battery technology development. Transport segment: Passenger cars and delivery vans <2 tons.

The average BEV marketed today allows a range of approximately 100 km per charge. It has been assumed that the nickel-metal hydride and the lithium-based batteries from about year 2005 will be able to offer 'affordable' range per charge of about 200 km.

From year 2010 the lithium-based technology is expected to offer about 300 km per charge. The daily distance travelled may in average be about 55 km/day (20000 km/year). Thus, a range of 300 km, on the fully charged battery, covers well 5 days needs for transport in average. However, due to battery costs the average BEV purchased beyond year 2010 may have less this range, in accordance with owner needs.

In the scenarios, the technical performance of the BEV batteries has been assumed constant beyond year 2010.

BEV market potential and market penetration assumed

From the above assumptions, the technical market potentials for the battery electric vehicle have been estimated. The BEV market potentials assumed for the period analysed is shown in Figure 5-6.

Combining the BEV range per charge offered, Figure 5-5, with the requirements on the market, Figure 5-4, the potential BEV market share can been estimated to about 20% for new cars sold in the period 2001-2005.

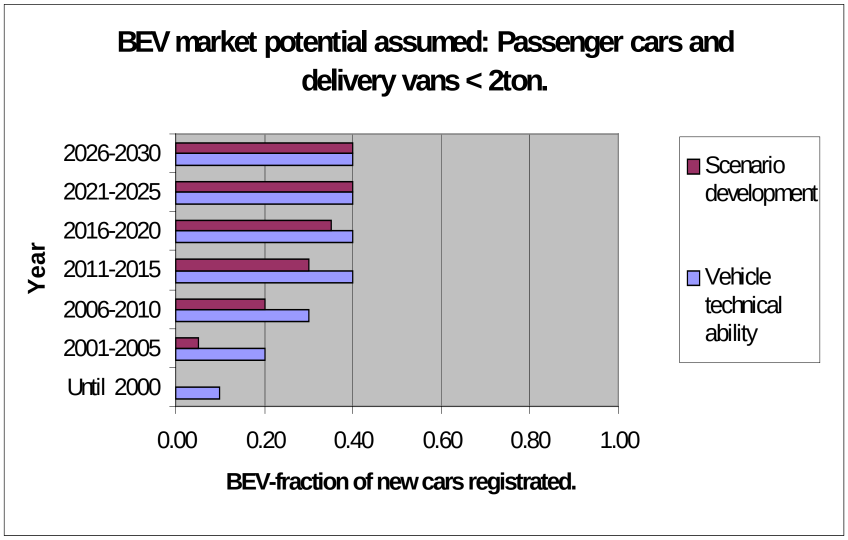

Figure 5-6 Scenario S1. Market potential and market penetration developments assumed for battery electric vehicles in road transport segment: Passenger cars and delivery vans < 2 tons.

During the period, range per charge increases for the new BEV's marketed, and the corresponding market potentials increase. For the period 2006-2015 it has been assumed, that about 30% of all new cars could potentially be of type BEVs, based on owner requirements and the BEV performance.

Beyond year 2015 the average new BEV sold is expected to offer 300 km per charge, and the corresponding market potential has been estimated to about 40%.

Figure 5-6 furthermore shows the market penetration of the BEV assumed for the scenarios S1 and S3. Beyond year 2020 the market penetration assumed covers the total potential market share of 40% for the BEV. On the shorter-term, for the period 2001-2005, it has been assumed that 5% of all new vehicles entering the fleet are BEVs.

5.2.3 HFCV market potential

The fuel cell vehicle may be expected first to be marketed in versions that includes onboard reformers for hydrogen production from e.g. methanol or gasoline. This reduces infrastructure constraints, and on-board hydrogen storage is not required.

In the scenario analysis, however, only the direct hydrogen fuel cell vehicle, HFCV, that offers zero-emission during operation, is considered. For this vehicle an onboard hydrogen store is required. For setting up the scenarios, focus is put on the vehicle range, and thus the onboard hydrogen storage capacity, to determine the potential future market for the vehicle.

FCEV range and on board hydrogen storage

Concerning the hydrogen storage development for onboard application, and the associated range for the defined average vehicle in the fleet segment focussed on, the assessment shown in Figure 5-7 is assumed for the scenario development.

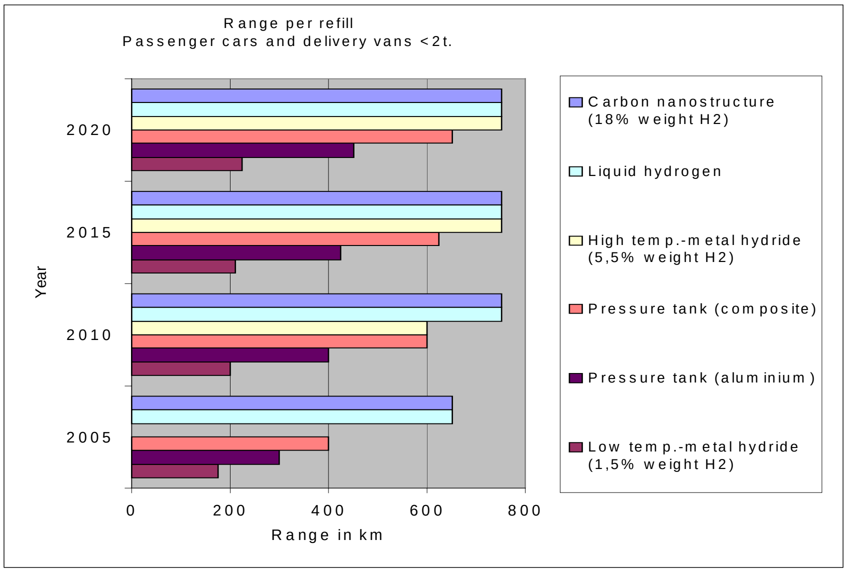

Figure 5-7 Hydrogen storage developments for onboard application, and associated average vehicle range per refill.

Year 2010 and onwards composite pressure tanks, high temperature metal hydride hydrogen stores, cryogenic liquid hydrogen tanks, and may be also the carbon nanostructure type of hydrogen storage, are expected to offer a range between refill of 600 km or more.

More than 700 km per hydrogen refill make the direct hydrogen fuel cell vehicle fully comparable in range to the conventional ICEV, using gasoline or diesel. For the scenario development it is assumed, that this range becomes available for the customer year 2015.

FCEV market potentials and penetration assumed

As shown in Figure 5-8, the potential market share for the HFCV beyond year 2015 could become 100% based on the technical performance of the vehicle only.

Many factors may, however, have reducing impact on the potential. Important such factors, off course, are the availability of European hydrogen supplies infrastructures, and the vehicle investment cost and operation costs for the owner.

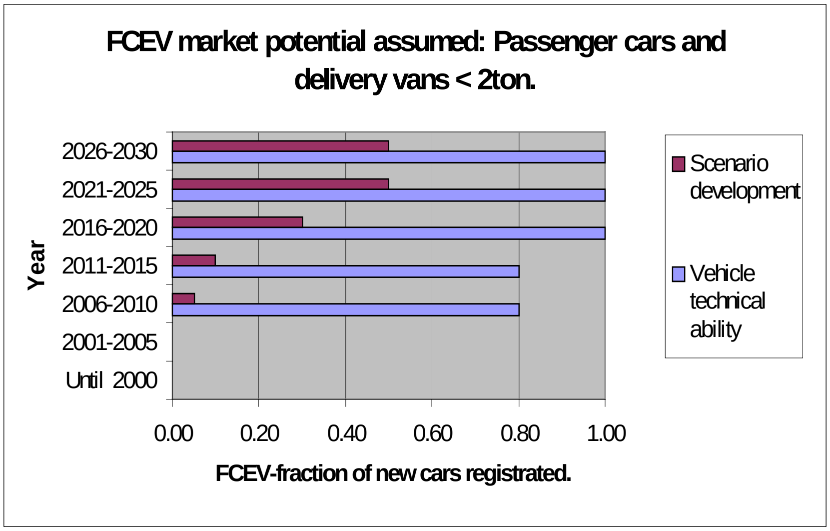

Figure 5-8 Scenario S2: Market potential and market penetration developments assumed for fuel cell based electric vehicles in the road transport segment: Passenger cars and delivery vans < 2 tons.

The assumed market penetration in the scenarios S2 and S3 is furthermore shown in Figure 5-8. Beyond year 2005 the HFCV is assumed first to enter the fleet. For the period 2006-2010 the FCEV is assumed to get a 5% share of the Danish market for new vehicles. This amounts to about 6500 vehicles per year entering the fleet for the period.

Beyond year 2015 the hydrogen infrastructure constraints are assumed to be limited. Beyond year 2020 the HFCV type of vehicle has been assumed to gain 50% of the Danish market.

The achievable HFCV fleet development in Denmark depends heavily on the development in neighbouring countries and in Europe as a whole. The car owner of today expects via the car to be able to travel anywhere in Europe. Therefore, hydrogen filling stations accessible in most of Europe, are required for the direct hydrogen FCEV to gain market shares as assumed.

5.3 Replacement rate in the Danish road transport fleet

In the scenario analysis the number of new vehicles entering the fleet, and the number of vehicles leaving the fleet, are calculated based on forecast data on the total size of the fleet, and based on the expected lifetime of vehicles in the fleet, as derived from statistics.

5.3.1 Expected development for the number of vehicles

The number of passenger cars and delivery vans of weight less than 2 tons in Denmark are shown in Figure 5-9. Up to year 1997 the figure shows statistics [6]. Onwards from this year, the figure shows forecast results on an expected long-term development in the vehicle stock, from The Danish Road Directorate [4].

The number of vehicles shown in Figure 5-9 relates to a population in Denmark of well 5 million people.

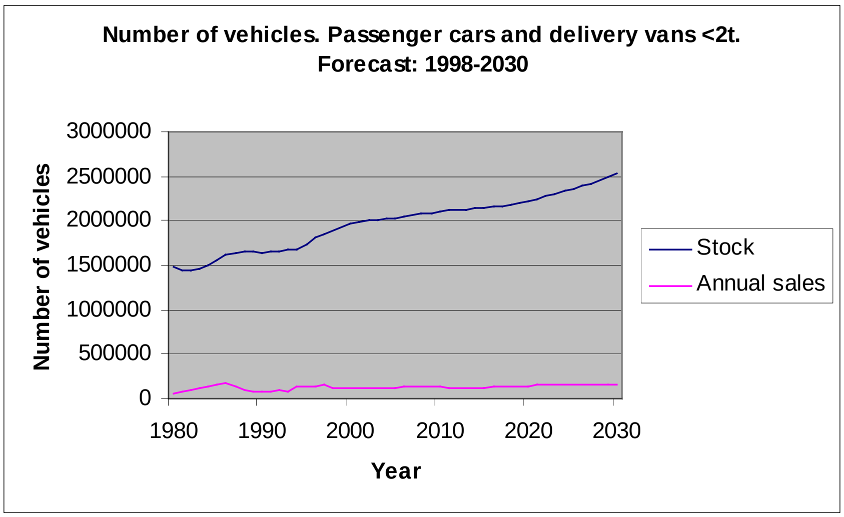

Figure 5-9 Numbers of vehicles. Transport segment: Passenger cars and delivery vans < 2 tons. Statistics until 1997. Onwards until 2030 forecast data. Source: [4].

The road transport segment considered amounts to about 2.0 million vehicles at year 2000. During the period this number is expected to increase. Year 2030 about 2.5 million vehicles are expected in this transport segment.

The number of new vehicles annually registered in Denmark in this market segment is expected to increase. The number is in order of magnitude about 150.000 vehicles in the period analysed. Historically, the annual sales have shown considerable variation. In the scenario analysis the annual sales are calculated, as consequence of an estimation of the vehicle age distribution in the Danish transport fleet.

5.3.2 Vehicle lifetime distribution

The vehicle lifetime in the fleet partly determines the overall renewal and vehicle replacements in the fleet.

For the Danish fleet, the average lifetime of cars has shown a moderate increase for some decades. However, for the scenario analysis it has been assumed, that the average lifetime for new cars entering the fleet is constant in the future, and equal to an estimated present level.

On average, the vehicle lifetime in the considered segment of the Danish road vehicle fleet can be set to 17.3 years for recent vintage groups. This level corresponds to Danish statistics until 1997. The detailed lifetime distribution assumed in the scenario analysis, for new cars entering the fleet, is shown in Figure 5-10.

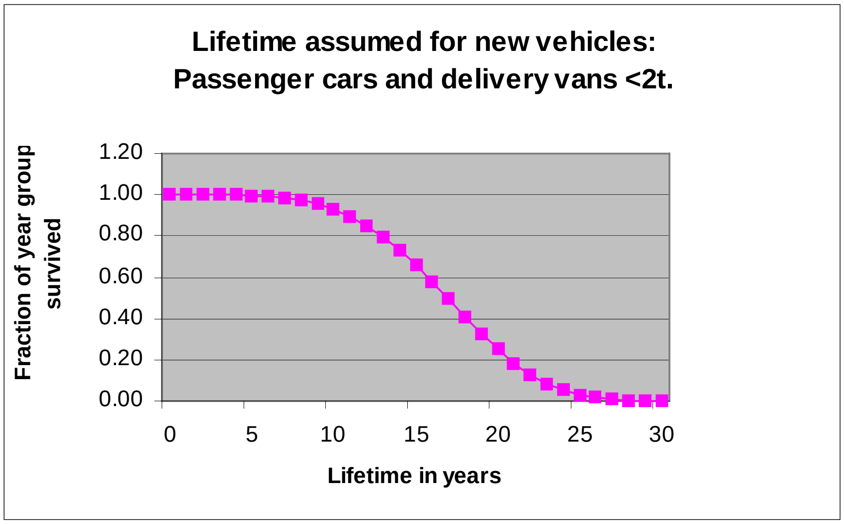

Figure 5-10 Lifetimes assumed for new passenger cars and delivery vans < 2 tons. Distribution 50% fractile: 17.5 years. (Mean value: 17.3 years).

The vehicle lifetime varies considerably in the Danish fleet, as reflected in the distribution shown in Figure 5-10. The vehicle lifetime for vehicles within the same vintage group varies from about 10 years and up to 25 years.

From the vehicle lifetime distribution, fleet statistics, and from the forecast of overall fleet size, the age composition of the fleet and its development is derived.

Such age distributions form basis for the further analyses of the fleet development and e.g. fuel consumption characteristics. Accumulated effects, e.g. due to technological developments during the period, are reflected in the analysis based on the age distribution development for the fleet.

Thus, the assumption shown Figure 5-10 has implications on e.g. the rate of penetration of new cars, new technology entering the fleet, and the characteristics of vehicles replaced from the road transport fleet.

5.3.3 Composition of vehicle age in the Danish fleet

Figure 5-11 shows the forecast data on the number of passenger cars and delivery vans < 2 tons for the Danish fleet. Furthermore the figure shows the expected development for the vehicle vintage composition.

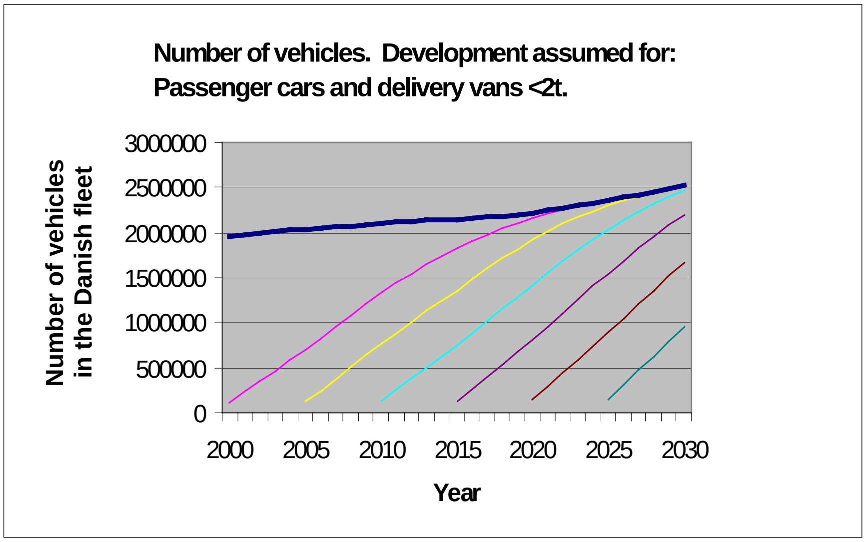

Figure 5-11 Development assumed for the Danish stock of passenger cars and delivery vans < 2 tons. Diagonal lines describe the accumulated number of new vehicles that have entered the fleet.

About 15% of the year 2000 vehicle stock have remained part of the fleet year 2015. New vehicles purchased since year 2000 have replaced most of the stock, as seen from Figure 5-11. In the scenarios part of these new vehicles is assumed to be electricity based vehicles, according to the assumptions made on the market penetration development for future vintage groups of BEV and HFCV.

5.4 Scenario model and difference analysis

A scenario model has been built to analyse road transport fleet developments based on disaggregated developments in defined fleet segments or transport sub-sectors. Outputs from the model focussed on in the analysis are the energy and emission consequences. Economic consequences of the scenarios developed have not been considered in this report. Focus is put on the

- Fleet composition development
- Fuel substitution consequences and
- CO_2 emission consequences.

Inputs to the model and the level of detail of the model are described in the previous sections of the report.

Scenarios developed, S1, S2, and S3 are compared to their respective reference scenario, i.e. the baseline development. The baseline forecast assumes the continuation in using the ICEV type of vehicle only.

The presentation of scenario results will include both the descriptions of consequences for the alternative vehicles entering the fleet, and descriptions of the consequences related to the ICEV vehicles substituted according to the baseline development. Thus results from each scenario will be presented as the difference analysis, where the alternative is compared to its associated reference development.

Results from the scenario model calculations are described in the following sections 5.5 (S1 scenario), 5.6 (S2 scenario), and 5.7 (S3 scenario).

5.5 S1: Scenario results for BEV

The BEV scenario, scenario 1, aims to integrate the most energy efficient technology for road transport in the segment considered, and to achieve maximum fossil fuel substitution and CO_2 emission reduction per vehicle. Furthermore, the aim is to reduce emission of air pollutants from road transport.

The battery electric vehicle technology, being the most energy efficient among the technologies considered, is promoted for rapid transport fleet integration. The limited range of the BEV limits the market potential. Year 2030 about 40% of the fleet, or about 1million vehicles are aimed to become BEVs in the scenario.

The BEVs have been aggregated in vintage groups each covering a 5-year period. For the individual BEV vintage group the average vehicle energy efficiency is assumed constant, throughout the vehicle lifetime. This is assumed for a group despite that e.g. the battery efficiency may decrease as the individual battery age, or the battery efficiency may improve due to replaced battery packs.

In general it has been assumed that individual vehicles do not age but will maintain the characteristics assigned to their vintage group throughout the lifetime of the individual vehicle.

5.5.1 S1: BEV fleet development and vintage composition

The overall fleet size development, and the number of BEVs accumulating in the fleet in the S1 scenario, is shown in Figure 5-12.

At the bottom of Figure 5-12 the overall BEV fleet build-up is shown. Furthermore, the BEV vintage composition in the transport segment considered is shown. Age groups, each covering a five years period, are shown. Along the period the number of BEVs within an age group decrease according to the lifetime distribution assumed. As seen from the figure, the BEV vehicles entering the fleet e.g. in the period 2006-2010 have almost by year 2030 left the fleet.

The fraction of the market for new vehicles, not covered by the BEV, is assigned to the ICEV in the S1 scenario. The ICEV fleet renewal and the age composition of the ICEVs in the fleet are not detailed in Figure 5-12.

In the S1 scenario, the BEV is introduced to the market in volumes beyond year 2000. The BEV market share of new vehicles sold in the period 2001-2005 has been assumed to be 5% as shown in Figure 5-6.

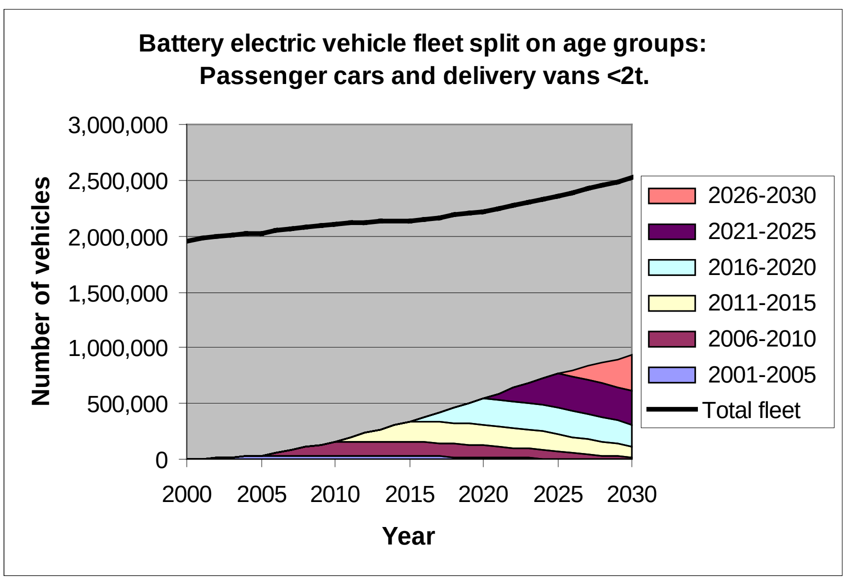

Figure 5-12 Numbers of vehicles and age group compositions in the battery electric vehicle (BEV) scenario development S1.

As consequence, according to the S1 scenario and as shown in Figure 5-12 the accumulated number of BEVs in the fleet ultimo year 2005 is about 1.5% of the fleet, corresponding to 29400 vehicles. Thus, in average for this period the annual sales of BEVs on the Danish market are almost 5900 vehicles per year.

By year 2010, the accumulated number of BEVs covers almost 7.5% of the vehicle stock. The annual average sales in the period 2006-2010 have increased to about 25000 vehicles per year, according to the S1 scenario assumptions.

Year 2020 more than 500000 BEV vehicles may be part of the Danish road transport fleet according to the scenario. The rate of increase in the BEV stock reduces slightly beyond 2025 due to BEVs ageing and BEVs leaving the fleet.

The number of BEVs accumulated in the fleet during the period up to year 2030 amounts to about 40% of the total transport segment analysed. In the S1 scenario, about 930000 vehicles are by then BEVs of different year groups.

5.5.2 S1: BEV consequences on fuel substitution

New BEVs substitute new ICEVs, that otherwise are purchased and entering the fleet in the baseline development. In a particular year the difference between the S1 scenario development and the baseline development is the accumulated effect of such changed purchase patterns.

The annual distance travelled in the defined average vehicle in the fleet is the same for both the alternative vehicle and for the reference ICEV, despite differences in the vehicle range per recharge or refill. Thus, long range per refill does not imply more annual driving, or visa versa. As mentioned earlier, the annual driving per vehicle decreases slightly through the period according to the baseline forecast data [4], and a typical range is close to 20000 km/year, or the equivalent of about 55 km/day.

Figure 5-13 shows the substitution in transport energy (at the vehicle) in the S1 scenario relative to the baseline development. The substitution of fossil fuel and the increasing consumption of electricity to charge the BEV battery packs are shown in accordance with the BEV fleet development described in Figure 5-12 above. Energy consumption characteristics of the individual BEVs entering the fleet, and the ICEV substituted, are shown in Figure 4-2 and Figure 4-1.

The fuels substituted (gasoline and diesel) increase almost linear as seen in Figure 5-13. The corresponding BEV fleet development shows likewise increasing electricity consumption, however towards the end of the period the rate begins to level out. This results from the expected BEV energy efficiency development, where new generations of BEV still show improvement, when at the same time the ICEV are assumed matured.

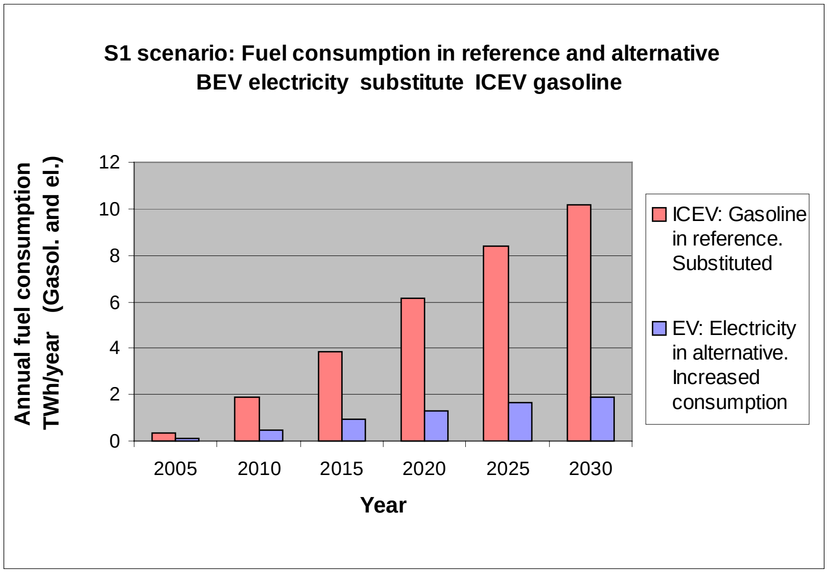

Figure 5-13 Fuel substitution developments. BEV electricity consumption in S1 and ICEV fuel substituted. Note: Gasoline and electricity are displayed in the figure.

From Figure 5-13 it is seen, that scenario S1 increases the electricity demand of about 2 TWh year 2030. This corresponds to an about 6% increase of the electricity demand the same year according to The Plan scenario, Energy21. (According to The Plan scenario, the Danish electricity demand is close to constant throughout the period analysed.)

The about 6% increase in electricity demand year 2030 is capable of operating about 40% of the Danish road transport segment, passenger cars and delivery vans < 2 tons, as BEVs. If e.g. wind power is to supply about 2 TWh of electric energy, then of about 600 MW installed wind power capacity is needed or about 300 offshore 2 MW wind turbines.

In the S1 scenario, about 11 TWh (or about 40 PJ) of fossil fuel is substituted year 2030 relative to the baseline development.

5.5.3 S1: BEV consequences for CO_2 emission

Despite the increased electricity demand to operate the emerging BEV fleet it is assumed, that the specific CO_2 emission per kWh delivered develops according to the Energy21, The Plan scenario [2], throughout the period.

For the reference scenario ICEV, the specific CO_2 emission per km travelled is determined from the energy efficiency of the vehicle and the type of fuel used, i.e. gasoline or diesel. For the individual ICEV vehicle the CO_2 emission per km travelled is constant throughout the vehicle lifetime. Furthermore, the characteristics of the fuel are assumed constant. The ICEV fleet may thus change its specific CO_2 emission in average, only as consequence of changes in the fleet composition, e.g. from the ongoing substitution of old vehicles with new ICEVs that may have energy efficiency improvements assumed.

For the BEV, the electricity charged change its CO_2 characteristics during the vehicle lifetime in accordance with the electricity supply system development. (Likewise for the individual HFCV. When hydrogen is produced via electrolysis based on electricity from the grid, the specific CO_2 emission per vehicle and km depends on the hydrogen supply system development.)

Figure 5-14 shows CO_2 emission consequences of the S1 scenario relative to the baseline development. As for the energy consumption, the CO_2 emission substituted from the baseline, via ICEV substitution, increases during the period following an almost linear development, as seen from the figure.

However, the CO_2 emission from the corresponding BEV fleet development levels out at about year 2025, and decreases from then on. This is due to the combined developments for the BEV energy efficiency development, and the development in the specific CO_2 emission per kWh of electricity produced according to the Energy21, The Plan scenario.

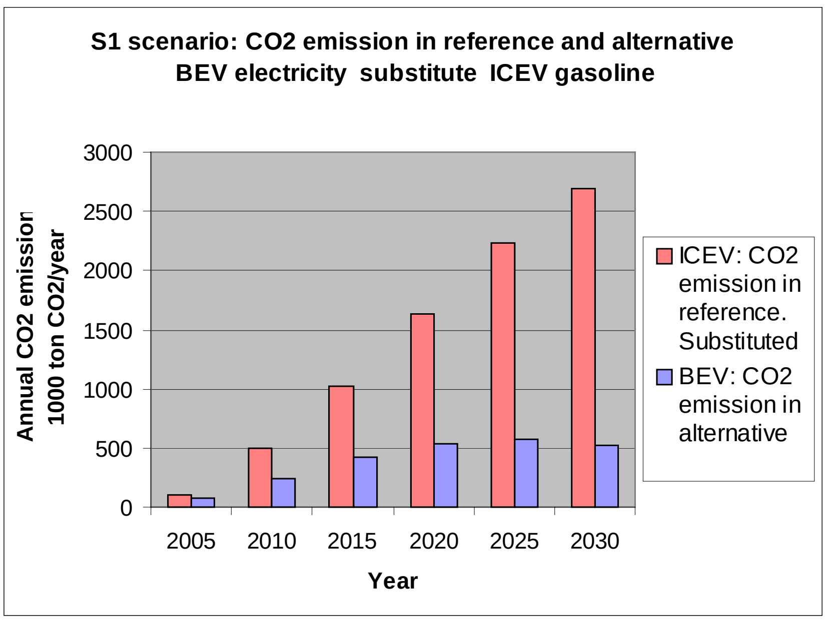

Figure 5-14 CO_2 emissions in scenario S1 and in the baseline development. Electricity production CO_2 characteristics: Development according to the Danish Energy21, The Plan scenario.

The overall annual CO_2 emission reduction year 2030 achievable in the S1 scenario relative to the baseline is about 2.17 million tons CO_2 per year. For the transport sub-sector considered, i.e. passenger cars and delivery vans < 2 tons, the baseline emission expected year 2030 is 7.28 million tons CO_2 per year. Thus, in the S1 scenario a CO_2 emission reduction of about 30% is achieved for the transport segment considered.

Relative to the expected baseline emission of 14.2 million tons CO_2 per year from the total Danish transport sector, the S1 scenario may contribute a reduction of well 15% year 2030.

5.6 S2: Scenario results for HFCV

The HFCV scenario, scenario 2, aims to integrate energy efficient road transport technology, with range per refill fully comparable to the conventional ICEV, in order to achieve substitution of fossil fuels and to achieve CO_2 emission reduction. Furthermore, the aim is to reduce emission of air pollutants from road transport.

The direct hydrogen fuel cell vehicle technology compared to the ICEV, is expected to offer energy efficiency and CO_2 emission gains beyond year 2010, and from then of the vehicle is promoted for rapid transport fleet integration.

Infrastructure build-up for hydrogen production and tanking is required. Year 2030 about 40% of the fleet, or about 1million vehicles are aimed to become HFCV in the scenario.

Infrastructure needs related to the scenarios are not analysed in this report, as mentioned earlier. Thus, options for a graduate transition towards new transport fuel distribution systems relevant for the scenarios are not described.

The possibility of gradually developing an infrastructure of smaller scale electrolysis based hydrogen refill stations for the HFCV fleet has been assumed implicitly. In segments of the road transport fleet in regular service, such as bus fleets serving regular routes, may be the first segments to introduce hydrogen, and such local infrastructures for hydrogen supply in urban areas may initiate the build-up of a hydrogen supply infrastructure covering larger regions.

For the HFCV to achieve high market penetration, the vehicle must be able to make the journey into most regions of Europe. The hydrogen supply infrastructure, therefore, must cover larger regions for the direct hydrogen fuel cell vehicle to gain substantial market shares.

As seen from Figure 5-8 the potential market share of the HFCV may be 80% beyond 2005 and 100% beyond 2015, based on the technical performance of the vehicle itself. However, in the scenario analysis the HFCV market introduction is assumed to take place beyond year 2005. For the period 2006-2010 a market share of 5% is assumed. For the period 2011-2015 a market share of 10% of new vehicles in the Danish fleet is assumed. However, beyond year 2020 the HFCV is assumed to cover 50% of the market.

Thus, a time delay exists in the assumptions, from the time of technical maturity of the HFCV, and to the HFCV market penetration. It is assumed that infrastructure build-up during that period is sufficient to be consistent with the assumed high HFCV market penetration beyond year 2015.

Issues concerning developing hydrogen supply infrastructures have been addressed, e.g. in the references [5], [8], [9], [12], [15],[18].

In this scenario analysis it has been assumed, that hydrogen is produced via electrolysis based on electricity from the Danish grid.

5.6.1 S2: HFCV fleet development and vintage composition

As seen from Figure 5-15, beyond year 2015 the HFCV rate of market penetration is assumed to increase. From then on the HFCV enters the fleet at a considerable rate in the S2 scenario. Beyond year 2020 it has been assumed that the HFCV has 50% of the market for new vehicles in the transport segment analysed.

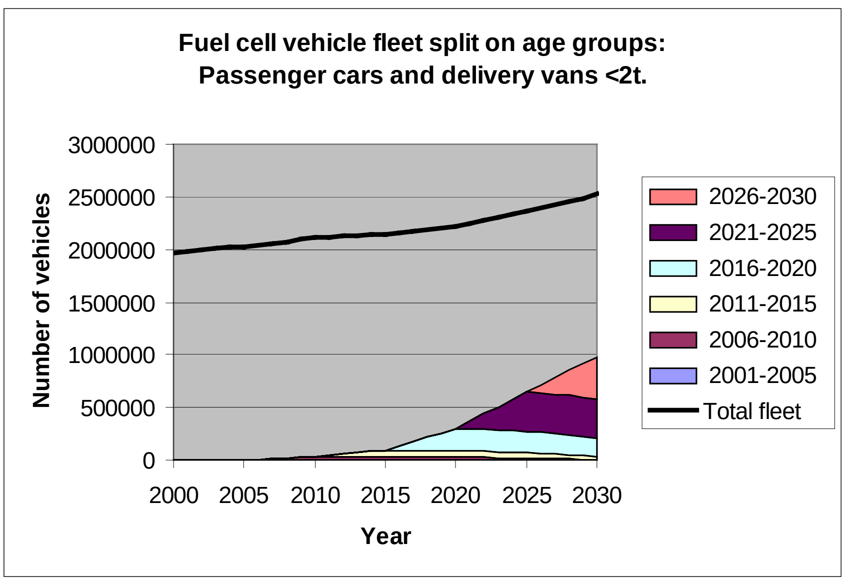

Figure 5-15 Numbers of vehicles and age group compositions in the direct hydrogen fuel cell vehicle (HFCV) scenario development S2.

Year 2030 about 980000 HFCV vehicles is part of the road transport fleet, or close to 40% of the total fleet segment, passenger cars and delivery vans < 2 tons, year 2030. This is close to the number of battery electric vehicles accumulated in the fleet in the S1 scenario, i.e. about 930000 BEV vehicles year 2030. An about 5% difference in HFCV and BEV fleet size.

5.6.2 S2: HFCV consequences on fuel substitution

Gasoline substituted from the baseline development, and the hydrogen consumption development according to the S2 scenario, are shown in Figure 5-16.

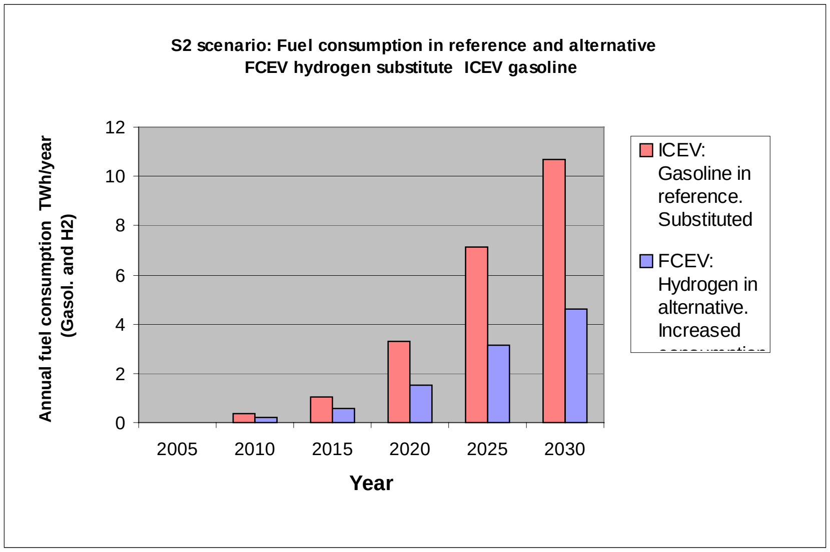

Figure 5-16 Fuel substitution developments. FCEV hydrogen consumption in S2 and ICEV fuel substituted. Note: Gasoline and hydrogen are displayed in the figure.

The hydrogen demand in the S2 scenario year 2030 has been calculated to 4.59 TWh/year hydrogen (HHV) or 16.6 PJ/year at the vehicles, as compressed hydrogen prepared for vehicle refill. The corresponding electricity consumption is about 5.4 TWh electricity, when the overall conversion efficiency, electricity to hydrogen stored onboard the vehicle, is included.

Gasoline substituted year 2030 amounts to about 10.69 TWh or about 38.5 PJ/year of gasoline.

5.6.3 S2: HFCV consequences for CO_2 emission

Hydrogen production via electrolysis is assumed. The overall efficiency, from electricity to hydrogen onboard the vehicle, has been set to 85% generally, and electricity for electrolysis is delivered from the Danish grid, where the CO_2 characteristics develop according to Energy21, The Plan scenario.

From these assumptions the CO_2 emission consequences of the S2 scenario, and the corresponding CO_2 substitution in the baseline development are shown in Figure 5-17 below.

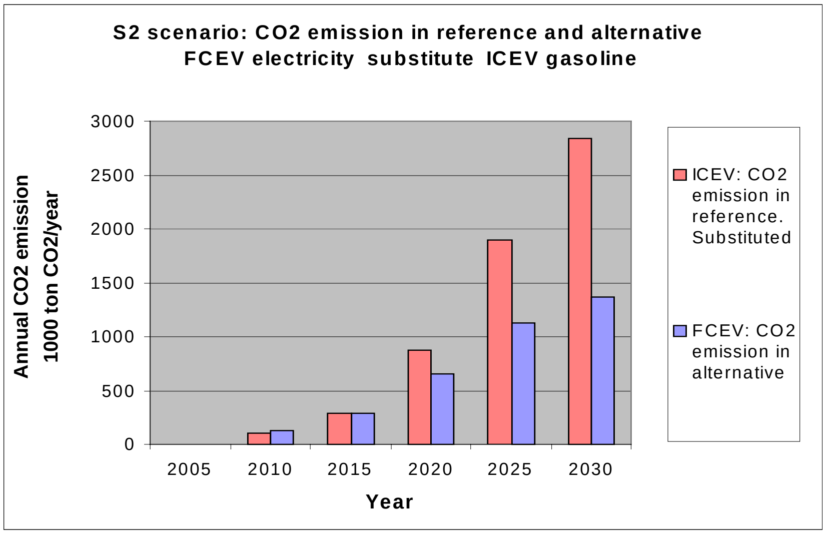

Figure 5-17 CO_2 emissions in scenario S2 and in the baseline development. Electricity production CO_2 characteristics: Development according to the Danish Energy21, The Plan scenario.

It is seen from Figure 5-17, that a substitution of the conventional ICEV by the HFCV is associated with an increased CO_2 emission up to about year 2010-2015. The electrolytic hydrogen production based on grid electricity involves CO_2 emission from the power supply system that exceeds the CO_2 emission from the corresponding ICEV.

Thus, the environmental gains from integrating the HFCV before year 2015 mainly concern reducing emissions of air pollutants. However, beyond year 2015 the CO_2 emission reduction gains start building up.

By year 2030 the CO_2 emission reduction in the S2 scenario, relative to the baseline development, amounts to about 1.47 million tons CO_2/year. The baseline CO_2 emission expected year 2030 from the transport sub-sector, passenger cars and delivery vans < 2 tons, is 7.28 million tons CO_2 per year. Thus, in the S2 scenario a CO_2 emission reduction of about 20% is achieved for the transport segment considered.

Relative to the expected baseline CO_2 emission of 14.2 million tons CO_2 per year from the total Danish transport sector, the S2 scenario may contribute a reduction of well 10% year 2030.

5.7 S3: Scenario results for BEV and FCEV combined

The combined BEV & HFCV scenario, scenario 3, aims to minimise CO_2 emission and the consumption of fossil fuels in the road transport sector by promoting high market penetration of the electricity based alternative vehicles. The aim is furthermore to reduce the emission of air pollutants from road transport.

Via the electricity based vehicles, BEV & HFCV, the flexibility of the electricity supply system to integrate renewable energy sources, such as wind power, and to reduce CO_2 emission, is transferred to cover segments of the transport sector as well.

The S3 scenario is composed from the S1 and S2 scenarios. Scenario S3 aims to half CO_2 emission by year 2030 relative to the baseline development for the road transport segment considered. Year 2030 almost 80% of the fleet, or close to 2 million vehicles are assumed to become electricity based BEV and HFCV vehicles.

5.7.1 S3: Market penetration assumed for BEV and FCEV combined

Due to the very low specific electricity consumption of the BEV, these vehicles are introduced in the S3 scenario. However, because of the limited range per charge compared to the ICEV the BEV market potential is reduced.

Beyond year 2015 the HFCV range per refill is expected to become fully comparable to the ICEV range. From then on, the HFCV market potential has no disadvantage relative to ICEV as to the vehicle range.

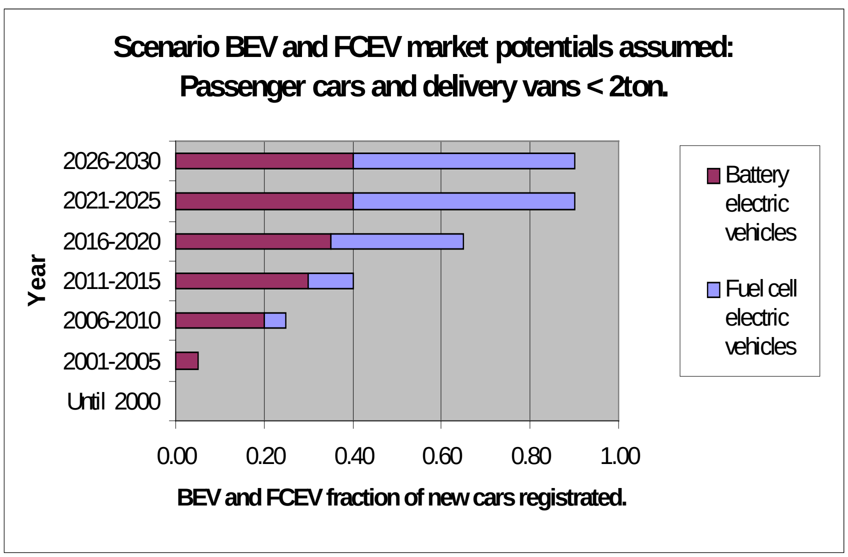

Figure 5-18 Scenario S3=S1+S2. Market potential and market penetration developments assumed for battery electric and fuel cell vehicles in road transport segment: Passenger cars and delivery vans < 2 tons.

As seen from Figure 5-18, the S3 scenario is the sum of the S1 and S2 scenarios. Market penetrations assumed for the BEV and HFCV are added to the S3 scenario market penetration for the electricity based alternative vehicles in the transport segment, passenger cars and delivery vans < 2 tons.

The battery electric vehicle is assumed first to gain a considerable market penetration. Beyond year 2020 the market share of the BEV has been assumed to saturate at 40% of the market for new vehicles.

The direct hydrogen fuel cell vehicle is assumed to emerge at the market beyond year 2005. However, not until year 2015 is the HFCV assumed to acquire high market penetration and volume sales. As for the BEV, the HFCV market share has been assumed to saturate beyond year 2020, but at a higher market share of 50%.

In the S3 scenario these developments leave behind an ICEV market share of 10% beyond year 2020. Beyond year 2020 it has been assumed that only 10% of new cars sold are of the conventional ICEV type of vehicle on gasoline or diesel.

5.7.2 S3: BEV and FCEV fleet development

The S3 fleet development and its composition (vehicle type and age) can be seen from Figure 5-12 and Figure 5-15, covering respectively the BEV scenario S1 and the HFCV scenario S2.

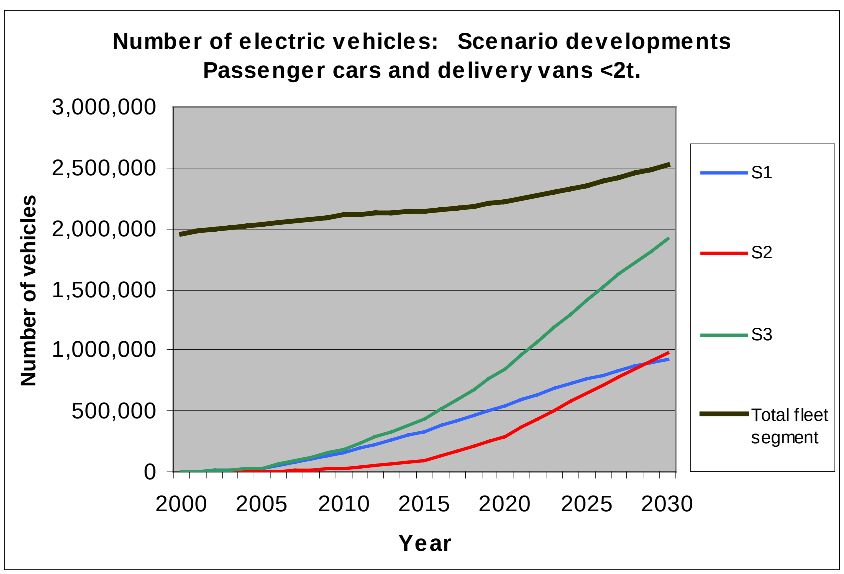

Figure 5-19 Numbers of vehicles in the scenarios S1, S2, and S3.

Figure 5-19 shows the development for the total number of alternative electricity based vehicles in the fleet and the forecast fleet development from [4].

Almost 2 million (1.91 million) alternative vehicles are part of the fleet year 2030. This is close to the total number of vehicles year 2000, of 1.96 million vehicles, in the transport segment, passenger cars and delivery vans < 2 tons.

In S3 year 2030 the percentage of alternative vehicles is 75.7% of the stock. Of these about the half are BEVs, and half are FCEVs, as seen in Figure 5-19.

Year 2005 about 1.5% of the fleet are BEVs, and virtually no HFCVs have entered the fleet. Year 2015 the electricity based alternative vehicles amounts to 20% of the fleet, of which 16% are BEV and 4% are HFCV.

5.7.3 S3: BEV and HFCV consequences on fuel substitution

An overview of the fuel substitution effects of the scenarios S1, S2, S3, is given in Figure 5-20. As indicated in the figure, the annual electricity consumption increase to operate the electricity based alternative vehicles is shown as positive values.

The fossil fuel substituted, which generally in the analysis is assumed to be 90% gasoline and 10% diesel, is shown in the figure as negative values, and the TWh energy unit refers to the energy content in the fuel.

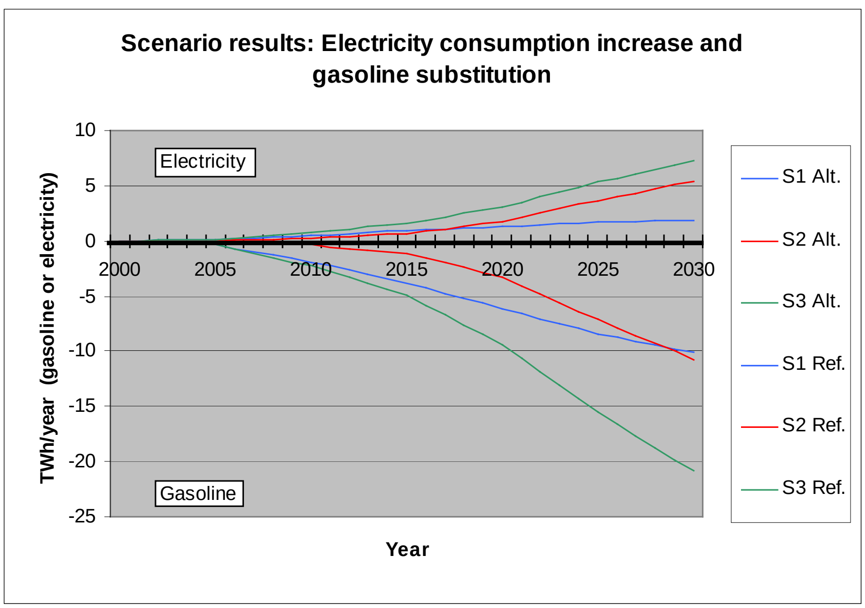

Figure 5-20 Fuel substitution developments. Increased electricity consumption in S1, S2, S3 and ICEV fuel substituted. Note: Gasoline and electricity are displayed in the figure.

Figure 5-21 below shows the development in electricity demand according to Energy21, The Plan scenario, and the resulting electricity demands when electricity to cover the transport scenarios S1, S2, and S3 are included.

From this Figure 5-21 and from the Figure 5-20 above, the consequences of the attractive energy efficiency of the BEV compared to the HFCV become very obvious. About the same transport service is delivered in the S1 and S2 scenarios. Each scenario covers approximately 1 million vehicles year 2030, and the electricity consumption to operate these fleets differs much as seen from the figures.

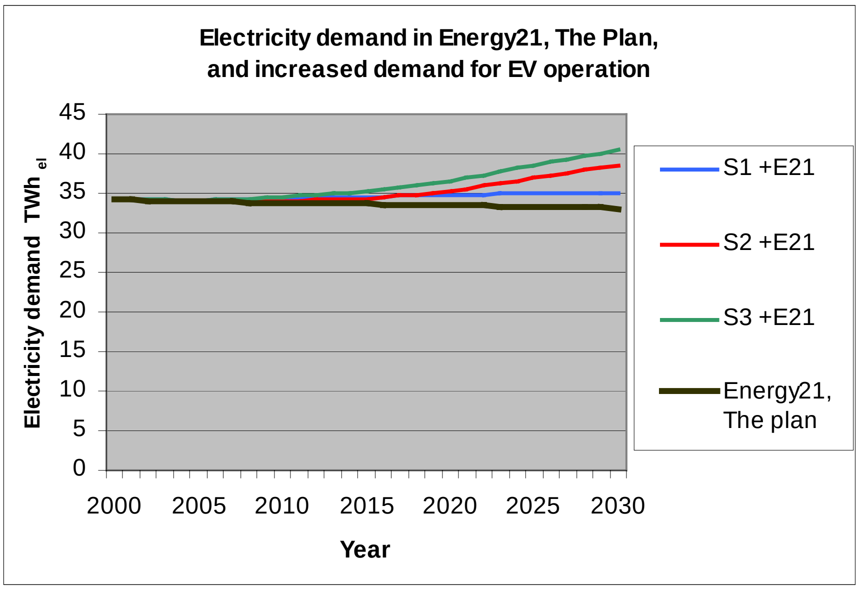

Figure 5-21 Developments for the electricity demand in S1, S2, S3, and the total electricity demand in Denmark according to Energy21, The Plan scenario.

Year 2030 the Energy21, The Plan scenario, expects an overall electricity demand of 33.1 TWh. Year 2000, the expected electricity demand amounts to 34.2 TWh, as shown in the figure.

To furthermore operate the BEV fleet year 2030, a demand increase of about 1.9 TWh is required as shown in Figure 5-21. Relative to the Energy21 baseline, this is a 5,7% demand increase. In S1 year 2030 the overall electricity demand thus increases to about 35.0 TWh/year.

To operate the HFCV fleet about 5.4 TWh is required, corresponding to a 16.3% increase in electricity demand. In S2 therefore, the overall demand year 2030 increase to about 38.5 TWh.

Taken together, as in the S3 scenario, the BEV and HFCV fleets year 2030 require 7.3 TWh of electricity, which equals a 22% increase in the demand, relative to the Energy21, The Plan scenario. The resulting overall demand increase to about 40.4 TWh/year in S3.

5.7.4 S3: BEV and HFCV consequences for CO_2 emission

In the present analysis, it has been assumed that the increased electricity demand to serve the BEV and HFCV fleets, can be met via the Danish power supply system, and that this extra supply has the same specific CO_2 emission per kWh produced, as in the Energy21, The Plan scenario. Based on this assumption the CO_2 emission consequences of the scenarios S1, S2, and S3 are shown in Figure 5-22.

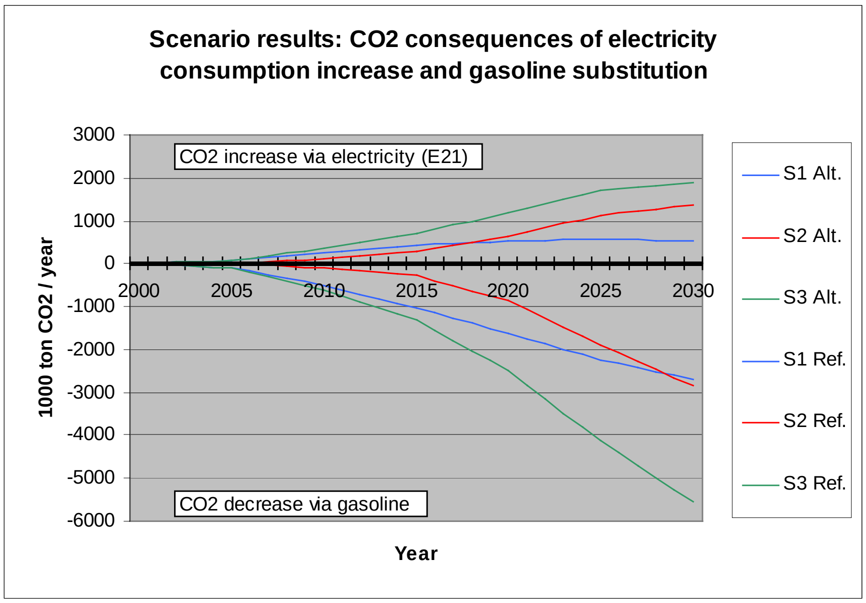

Figure 5-22 CO_2 emissions in scenarios S1, S2, S3, and in the respective baseline developments. Electricity production CO_2 characteristics: Development according to the Danish Energy21, The Plan scenario.

The presentation in Figure 5-22, for the CO_2 substitution consequences, is analogous to the Figure 5-20, presenting an overview of fuel substitution consequences of the scenarios. Comparing the figures it can be noticed from Figure 5-22, that the CO_2 emission curves related to the vehicle electricity supply level off towards the end of the period analysed.

This reflects the decreasing specific CO_2 emission per kWh_{el} in the Energy21, The Plan scenario, in the period analysed and as described in Figure 4-4. This reduction in specific CO_2 emission for the power supply is mainly a consequence of a steady development towards large-scale integration of renewable energy sources, and in particular wind power and biomass, in the Energy21, The Plan scenario.

In Figure 5-23 below the overall CO_2 emission reductions achieved relative to the baseline development are shown.

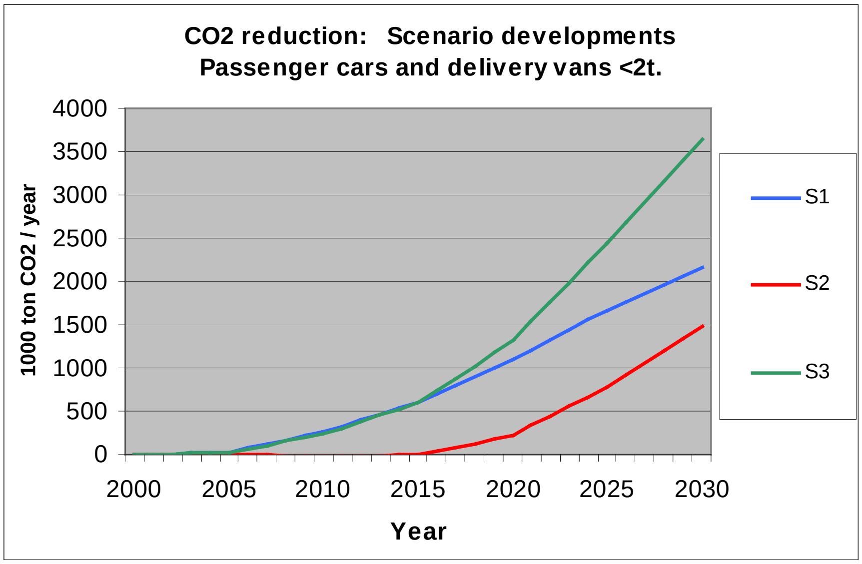

Figure 5-23 CO_2 emission reductions achieved in scenarios S1, S2, S3, relative to the baseline development. Electricity production CO_2 characteristics: Developments according to the Danish Energy21, The Plan scenario.

Year 2030 the CO_2 emission reductions achievable via the S1 and S2 are about 2.17 million tons CO_2 per year and 1.47 million tons CO_2 per year respectively. In the combined scenario S3 the reduction amounts to 3.64 million tons CO_2 per year.

The baseline CO_2 emission expected year 2030 from the transport sub-sector considered, passenger cars and delivery vans < 2 tons, is 7.28 million tons CO_2 per year. Thus, in the S3 scenario a CO_2 emission reduction of 50% is achieved relative to the baseline forecast [4].

Relative to the expected baseline CO_2 emission of 14.2 million tons CO_2 per year from the total Danish transport sector, the S3 scenario may contribute a reduction of about 26% year 2030.

5.8 Summary on scenario results

The main results from the scenario analyses are shown in Table 5-1. The main results focussed on are the fleet development for electric based alternative vehicles, substituted fuel in the scenarios relative to the baseline development, and the overall system CO_2 emission consequences.

Table 5-1. Main results for scenarios S1, S2, and S3, year 2015 and 2030. Danish transport sub-sector: Passenger cars and delivery vans <2 tons. Power supply according to Energy21, The Plan scenario.

Scenario	**S1**		**S2**		**S3**	
Year	2015	2030	2015	2030	2015	2030
Transport fleet developed						
BEV&HFCV, # vehicles	337.000	930.000	93.000	980.000	430.000	1910000
Fuel/Power substitution						
ICEV fuel substituted,TWh	3.86	10.14	1.06	10.69	4.92	20.83
El. demand increase, TWh	0.94	1.90	0.66	5.40	1.60	7.30
Overall CO_2 reduction						
1000 tons CO_2/year	599	2168	-4	1471	595	3640
% of sub-sector	9%	30%	-0%	20%	9%	50%
% of total transport	5%	15%	-0%	10%	5%	26%

Fuel substitution shown in Table 5-1 relates to the transport sector, where the consumption of conventional fuels, gasoline and diesel (expressed in TWh's in the table), is reduced on the expense of an increased consumption of electricity to operate BEV and HFCV fleets.

The alternative BEV and HFCV fleets provide the same transport services as the respective baseline or reference ICEV fleets. The overall transport service produced is unchanged going from the baseline situation to the alternatives.

From the table it is seen, that the BEV alternative is considerably more energy efficient than the baseline ICEV. The S1 scenario year 2030 shows that the BEV fleet using 1.90 TWh of electricity (ab grid) may substitute 10.14 TWh of conventional fuel (gasoline/diesel). Taking into account, that such comparison involves the two energy qualities, electricity and gasoline/diesel, this still reflects the considerable energy efficiency difference between the new BEV drive train and the conventional ICEV drive train. It must be emphasised, however, that the conventional ICEV defined in the baseline development [4] is the expected development for ICEVs in the Danish fleet, and not an ICEV development optimised for energy efficiency, as described in section 4.1.

The BEV and HFCV alternatives offer zero emission of air pollutants during operation, and CO_2 emission reduction potentials according to the CO_2 characteristics of the power supply system in question.

The CO_2 emission reduction consequences shown in Table 5-1 are based on the assumption, that the CO_2 characteristics of electricity during the period analysed develop in accordance with the power supply system described in Energy21, The Plan scenario [2].

Relative to the baseline CO_2 emission from the transport sub-sector considered, passenger cars and delivery vans < 2 tons, the S3 scenario may provide a 50% reduction of the CO_2 emission by year 2030, as seen from the table.

This reduction amounts 3.6 million tons CO_2/year. Relative to the expected baseline emission from the Danish transport sector in total, the S3 reduction amounts to 26%, as seen from Table 5-1.

Year 2015 the S3 scenario may contribute an about 5% reduction in CO_2 emission from the Danish transport sector in total.

6 EVs and the electricity sector

In the present scenario analysis it has been assumed that energy to operate the fleets of BEVs and HFCVs is supplied from the Danish electricity grid. The individual BEV recharges directly from the grid and the HFCV refills its hydrogen store on board the vehicle with hydrogen produced via electrolyses using power from the grid.

Issues adressed in this section concern the power transmission and distribution capacity of the Danish grid relative to demands in the scenarios S1, S2 and S3. Furthermore the ability of the electricity based BEV and HFCV vehicles as to utilise a fluctuating electricity production, such as wind power is adressed.

Load management options offered by a BEV or HFCV fleet are adressed. The relevance of introducing metering by the hour and a two-way communication system to continously inform consumers on the electricity price development is discussed as a mean to mobilise the load management options as elements in the power system regulation. Potential BEV interaction with a liberalised power exchange to supply power regulation to the market is described, and achievable gains for the BEV owner on a set up baseline power exchange are described.

Furthermore, the wind power capacity needed to generate the energy required to operate the BEV and HFCV fleets in the scenarios is described.

6.1 Transmission capacity to serve EV fleet

BEVs charging in the peak load periods may substantially increase the demand for power production capacity and grid capacity. Likewise, electrolysis for hydrogen production in peak periods must be avoided. Peak power production is costly and a demand increase in the peak periods may furthermore require expensive grid extensions.

It is thus important that BEVs are not charged during peak load periods. Sufficiently large battery packs can enable the BEVs to operate during the day without recharging batteries. The electricity system request for efficient off-peak charging thus coincide with BEVs owners desire for long range per charge. Developing affordable battery packs of sufficient energy capacity is important seen from a power system point of view.

Figure 6-1 shows a characteristic load profile in the Danish electricity system for a weekday in wintertime. In wintertime the electricity consumption is high. However, during nighttime the consumption is low in general in the Danish system. The maximum or peak power demand in the system is about 6.5GW. This level of the peak demand is not expected to change significantly in the future.

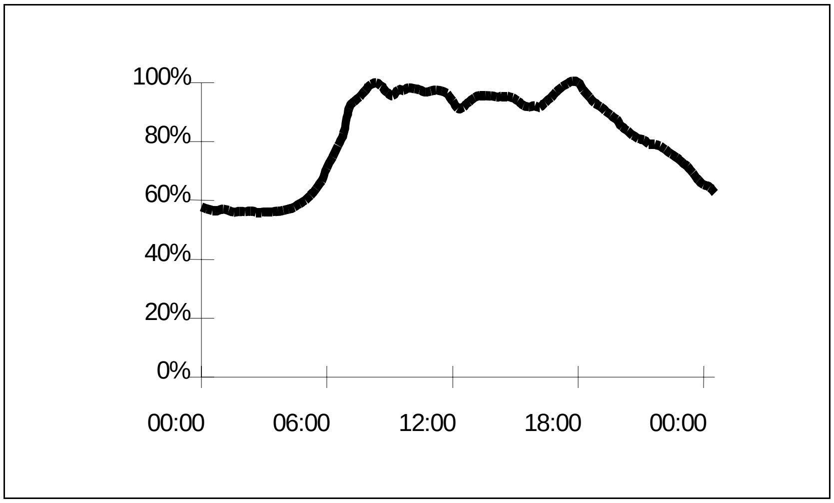

Figure 6-1 Relative variation in electricity load during 24 hours. Profile typical for a weekday in wintertime in the Danish electricity system.

In weekends at wintertime the peak power demand is reduced to about 85%. At a typical weekday in the summer period the peak demand is reduced about 20% relative to the winter peak, and in summer weekends the peak demand is reduced even further to about 60%.

Thus, as for most European electricity networks the Danish power transmission and distribution system has considerable off-peak capacity available that could support fleets of BEV and HFCV.

The order of magnitude of this transmission and distribution capacity available for further off-peak electricity supply in the Danish system is illustrated in Figure 6-2.

Figure 6-2 illustrates the potential additional loads that can be supplied via the present grid in the Danish power system. The additional load has been constrained by requiring that the total load in the off-peak periods is to stay below, say 5GW or 6GW, as shown in Figure 6-2. The estimates are based on electricity consumption patterns expressed in annual load duration curves for the present consumption.

As seen from the figure an additional off-peak load of 1GW can be applied for well 5000hours/year. Thus, more than 5 TWh/year can be supplied without increasing the total load in off-peak periods above the chosen 5GW upper limit. Staying below a 6GW limit in off-peak periods the 1GW load could increase consumption to about 7 TWh/year and thus get a load factor of about 7000hours/year.

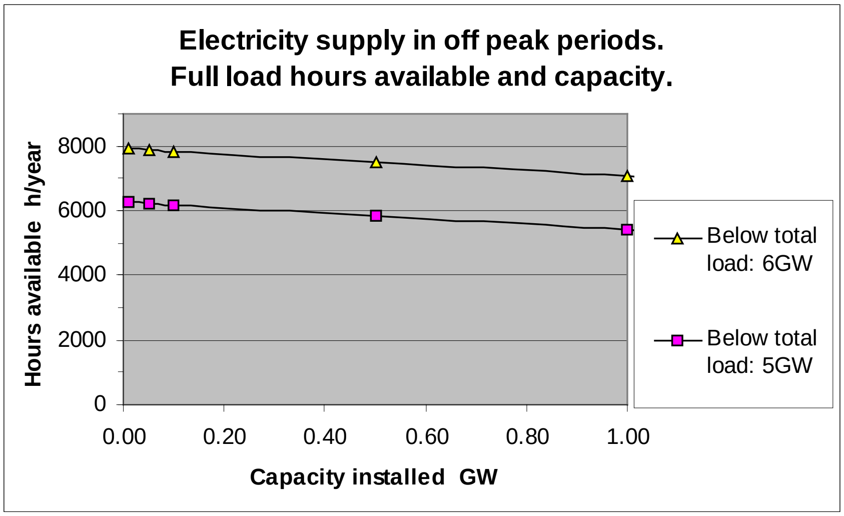

Figure 6-2 Electricity supply capacity available in off-peak periods in the Danish power supply system. Constraint assumed: Total load in the off-peak periods stays below 5GW or 6GW. (Peak load assumed: 6.5GW)

If a level of peak consumption was maintained throughout the year an additional production of about 20-25 TWh/year could in theory be generated and distributed in the system. This corresponds to an about 70% increase relative to the present annual consumption.

The grid capacity of course depends strongly on where and at which voltage the additional loads are connected. The following remarks serve to illustrate orders of magnitude of the increased electricity loads associated with the set up scenarios year 2030, and the S3 scenario in particular, that includes a conversion to electricity based operation of about 75% the future fleet of passenger cars and delivery vans in Denmark.

Grid capacity and the BEV scenario S1

Figure 6-1 and Figure 6-2 illustrate that a large transmission and distribution capacity within the present Danish system is available in the off-peak periods. This capacity is large compared to the needs of the BEV development in scenario S1 year 2030 (1.9 TWh) when charging during the night off-peak periods is assumed.

Less than 220MW of continuous supply may recharge the total BEV fleet year 2030, if the load is assumed constant throughout the year. This amounts to about 240W per BEV vehicle in average.

The BEV recharge capacity may be of the same order of magnitude as the discharge capacity. However, for residentially located recharge from the grid the capacity may be about 10kW per BEV. The annual electricity consumption for the average BEV year 2030 (of about 2040 kWh/year) may thus be recharged in only 204 hours (or 8.5 days) in total per year. These 204 hours per year equals about 4 hours/week or about half an hour per day (or about 2-3 % of the time).

If year 2030 all BEVs in the fleet (930000 BEVs) recharge simultaneously this could draw a load of about 9.3 GW, and the daily consumption in average in the fleet could in theory be recharged in about half an hour. If well 10% of the BEV fleet are connected to the grid in average and recharge simultaneously, the maximum load drawn may be close to 1GW from the BEV fleet. At 1GW of capacity the daily consumption in average may be recharged in 5.2 hours/day, and the annual consumption of electricity in the BEV fleet may be charged in 1900 hours per year.

Such 1900 hours per year for a 1GW load can without problems be supplied during the off-peak periods as seen from Figure 6-2. If well 20% of the BEV fleet are grid connected at locations for 10kW recharge a maximum load of about 2GW can be initiated, and such load applied for 2.6 hours/day in average or 950 hours/year may likewise power the BEV fleet in the S1 scenario year 2030.

Grid capacity and the HFCV scenario S2

Comparing Figure 6-2 to the scenario S2 electricity needs year 2030 (5.4 TWh), for electrolytic hydrogen production for HFCV fleet operation, it is seen that off-peak transmission capacity for this additional load exists today.

If the hydrogen production is to operate continuously an electric capacity of about 600MW is required as a minimum. If a hydrogen production plant of 1GW electric capacity were installed, however, the same hydrogen production would require 5400 full load hours. This delivery could be achieved outside the peak periods and without increasing the load above 5GW in the off-peak periods, as seen from Figure 6-2.

Grid capacity and the S3 scenario

In scenario S3, the sum of the S1 and S2 scenario developments, the electricity need amounts to about 7.3 TWh year 2030. This corresponds to an about 20% increase of the present electricity consumption in Denmark. Assuming hydrogen production facilities operated at a load factor of 5400 hours/year (for $1GW_{el}$ electrolysis plants in total) the present supply system will still be able to meet the further load from the BEV fleet (of 1.9 TWh/year). This can be seen from Figure 6-1 and Figure 6-2. Despite the 1GW load to power the scenario S2 hydrogen production, that occupy parts of the potential off-peak supply, more than 5.2 hours per day for an additional 1GW load is available to operate the S1 scenario BEV fleet. This is the case even at a high load weekday in wintertime as seen from Figure 6-1.

6.2 Metering by the hour

To convey the electricity consumption towards the off-peak periods and to mobilise regulation capacity on the demand side of the electricity system, it is essential that the individual consumers have the ability to adjust their demand according to e.g. an electricity price at hourly basis. This can reduce electricity purchase costs for the consumer, and the electricity supply can achieve cost reductions related to e.g. investments in peak electricity production, transmission and distribution.

Two-way communication systems are needed to connect the consumer and the power supply to achieve such benefits. The individual consumer or consumer groups must have access to a dynamic tariff system or direct access to electricity spot and balance market prices to mobilise this potential regulation capacity on the demand side of the system. Two-way communication systems can enable the consumer to react on (or interact dynamically with) electricity prices, that reflect power regulation needs in the overall system.

Installation of a two-way information system and hourly meetering at the individual consumer has been much discussed e.g. in Norway [11], [17]. This discussion has arised due to peak supply deficits experienced in parts of the Norwegian system. Events of extremely high spot market prices at the Nord-Pool power exchange have furthermore indicated capacity deficits emerging in the Scandinavian power systems in situations of particular cold weather during wintertime.

Trading and metering on an hourly basis enable capacity aspects as well as energy aspects to be handled through a market. Two-way information systems can mobilise load management options at the consumer, e.g. via postponing electric water heating and operation of washers to the off-peak period. Installing such systems may be cost-effective compared to an extension of the supply capacity to reduce peak capacity problems in the system.

Dynamic tariffs or market prices have potential to redistribute the consumption and production towards the most cost-effective periods for the system. Flexibility in different parts of the system may have potential to generate an economic benefit to the respective system actors. Flexibility may achieve its market value at the hour, and new options for power regulation in the system may emerge or be mobilised.

A two-way information system may correspondingly mobilise the large power regulation capability, which a fleet of electric vehicles constitutes due to its load flexibility.

BEV flexibility

To recharge the BEV the vehicle has to be connected to the grid somewhere of about 2-3% of the time at minimum. However, at when recharging must take place much depends on the energy capacity of the BEV battery and driving patterns of the owner e.g. during the week. Large BEV battery packs may enable that recharging is done only once or twice a week.

The grid-connected period can to a large extend be arbitrarily placed in time as long as the BEV battery state of charge meets the requirements of the owner. The individual BEV may stand connected to the grid for periods that add up to e.g. 10 fold or more of the minimum 2-3% of the time. Thus, the BEV has flexibility to postpone consumption for considerable periods of time and wait for favorable low electricity prices to occur.

This load flexibility of the BEV is valuable in the power supply system. As mentioned above, such demand side regulation capability may be integrated in the overall power system balance, if appropriate two-way communication systems are available.

A BEV fleet, and electrolysis plants serving a HFCV fleet, have considerable load flexibility which may be utilised via a dynamic power pricing system. The load management potentials that emerge by expanding these consumer segments can become substantial. Such increased flexibility on the consumption side of the system can compensate a reduced flexibility on the supply side of the system, and therefore increases the ability of the system to integrate a less flexible electricity production, such as the production from wind power.

A further power regulation possibility via the BEV is integration of the BEV battery as part of the peak power supply in the overall system. Grid-connected vehicles may contribute to the peak power supply via battery discharge to the grid. Such options have been considered e.g. in [20]. Whether this becomes an option for the individual BEV depends on the design of the power conversion in the vehicle and at the grid connection. The viability hereof furthermore depends on the charachteristics of the BEV battery in question. Such options are not included in the analysis in the following section, where a potential BEV interaction with a power exchange is addressed.

6.3 BEVs and a liberalised electricity market

The ability of the BEV to achieve an economic gain from utilising its load flexibility has been analysed relative to a liberalised electricity spot market. The analysis furthermore addresses the potential economic gain, which a BEV owner may achieve from trading on an electricity balance market, from selling the BEV regulation capability on such a market.

Baseline electricity exchange

The baseline electricity market assumed for analysis of the BEV interaction with a liberalised market is based on [1]. The set up baseline market model for sale and purchase of electricity includes the power systems in Northern Europe year 2005.

The baseline market set up comprises a spot market and a balance market for electricity. The structure chosen for the baseline spot market for year 2005 is close to the structure of the existing Nord Pool electricity market and the structure of the balance or regulatory market is close to the existing Norwegian model.

At the spot market sales and purchase of electricity are traded for the next 24 hours period. Producers and consumers state their offers daily before noon (12 a.m.) concerning prices and amounts for delivery in the forthcoming period from 0 a.m. to 12 p.m. Thus, offers are given 12-36 hours before the delivery. Based on these offers the spot market prices are determined by demand and supply on an hourly basis for the next 24 hours period.

Deviations from the planned trade at the electricity exchange spot market relative to the actual delivery and consumption in (and during) a particular hour are handled by the balance market. The electricity balance market must continuously secure the balance between power production and consumption. The balance market determines the price of short notice power regulation in the system and handles the necessary trade of power regulation based on received offers on short notice regulating (up and down) from both producers and consumers in the market.

Detailed model calculations on the North European electricity production system and data from the existing Nord Pool electricity market form the basis for the set up baseline market. Using the EMPS model (Samkøringsmodellen), calculations have been carried out to determine expected electricity price levels and the power exchange among the North European electricity systems during year 2005. The model operates with a time resolution of weeks, based on inputs concerning e.g. power plants, fuel prices, hydro inflow statistics, and power demand. Conversion of the calculated price levels on a weekly basis to baseline spot market prices on an hourly basis is carried out subsequently. This is done based on a statistical analysis of the observed hourly price variations at the Nord Pool spot market.

The corresponding baseline balance market is set up using a relation which is estimated from the balance market prices observed at the Norwegian electricity exchange. The estimated balance market prices are functions of the spot market price at the hour and the amount (and direction) of the short notice power regulation required at the market.

BEV trading at the spot market

Typically EVs charge batteries during the night, a time when electricity prices are low due to low loads. However, to benefit fully from the varying electricity spot market prices, which customers may have direct access to in the future, domestic electricity metering on an hourly basis is required. As mentioned above, this enables BEV owners to suspend charging until favourable low electricity prices occur. As future BEV battery packs are expected to increasingly prolong the driving range per charge (and thus increase the market for BEVs) battery recharge may no longer be required on a daily basis.

Figure 6-3 shows the variation of the electricity spot price on an hourly basis during a typical week at the set up baseline market for year 2005.

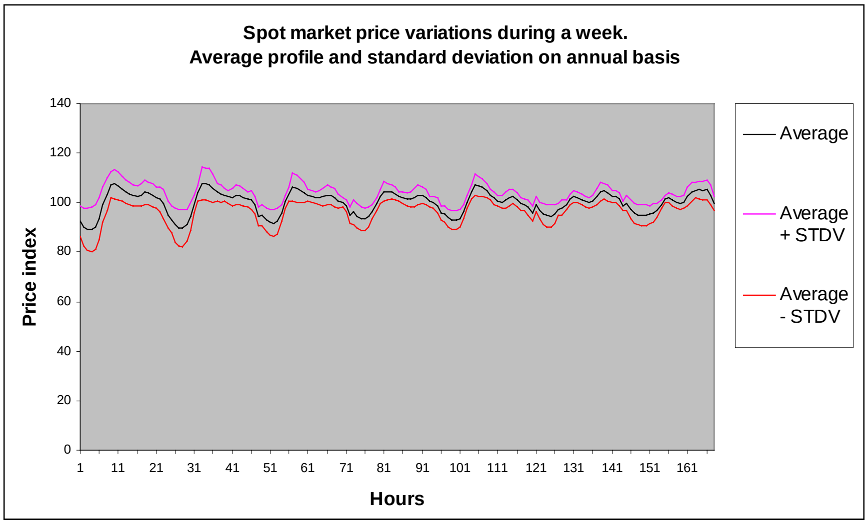

Figure 6-3 Price variations during a week on the baseline electricity spot market assumed for year 2005. Index 100 = price average.

Simulations of BEVs interacting with this baseline spot market for electricity and carried out using the ES^3 model show, that the load flexibility of the BEV can be used to lower purchasing costs of electricity (excluding tax) about 5% relative to the average spot market price year 2005 [1].

BEV trading at the spot and balance markets

The power regulation capability of the BEV, or of any other flexible electricity consumer (e.g. electrolysis plant with load factor adjusted), may be illustrated by the following example.

When charging the BEV from the grid, assume that this is planned at half the maximum capacity available from the BEV grid connection, and assume that this electricity purchase is planned on the spot market. A fraction of the BEV fleet may have chosen this opportunity for a particular hour. This fraction of the fleet, therefore, have the capability during charging to regulate up the consumption by 50% of its total capacity for charging from the grid, on the premise that the state of charge of the battery allows this. Likewise, these vehicles may have the capability to stop charging and thus to reduce the load at the hour from the spot market, of an amount equal to 50% of the capacity for charging from the grid. Such potential deviations from the planned trade on the spot market may be initiated from system balance, and are handled via the balance market.

Thus, from the demand side only, an individual BEV following this pattern for charging may in limited periods be able to contribute power regulation in both directions at a balance market. Such organised charging for a BEV fleet, based on a two-way communication system, may contribute substantial regulation capability to the system.

Detailed simulations show, that a battery pack capacity in the BEV of about 200 km/charge may enable owners to purchase a substantial part of the electricity from the balance market, and annual savings of more than 10% may be achieved at the set up baseline market.

Consequently, development towards increased utilisation of BEVs for transport has the potential to increase the supply of active power regulation capability on a future balance market. The capability of the overall electricity system to integrate fluctuating electricity production that requires power regulation, such as wind power, therefore increases. The power regulation potential from a BEV fleet may become substantial, and even a few percent of BEVs in the transport vehicle fleet can constitute an important player on the electricity balance market.

Technologies such as electric vehicles can increase the supply of power regulation on the market at prices on a level with the balance market. Thus, if large quantities of fluctuating electricity production (e.g. wind power) build up a strain on the future balance market, such technologies can form backstop prices on this market.

It must be observed, though, that from the point of view of the individual BEV owner the economic incentive is small. The economic gain from selling the BEV load flexibility or power regulation capability only, may not cover all costs associated with installing a two-way communication system at the consumer.

6.4 EVs and wind power

Integrating a fluctuating power supply, such as wind power, in the peak load period may not involve power regulation constraints to the same extent as the integrating of such production in the low load periods. Large wind power inputs in the low load periods during nighttime are more likely to conflict with base load production units with reduced power regulation capability. Thus EV charging during the night may contribute to counteract such potential constraints in the power system.

Danish offshore wind power may in the future supply a major part or all of the transport energy needed to operate the BEV and FCEV fleets in the scenarios. Power regulation requirements related to integrating such wind power resources may furthermore be compensated by the substantial load management flexibility offered by the BEV fleet and electrolysis plants supplying the FCEV fleet.

In the context of a liberalised electricity market wind-generated electricity is sold at market terms as any other electricity produced. The predicted production (12-36 hours in advance) from wind generators may be sold at the electricity spot market. However, the predictability of the wind power influence the market value of the wind-generated electricity. If the amount of wind-generated electricity offered by the producer at the spot market deviates from the later actual delivery then this discrepancy (surplus production or absent production) must be settled on the balance market. Therefore, the ability of the BEV and HFCV fleets to locate their electricity trading at the balance market at prices on a level with competing actors offering power regulation on the balance market determines the contribution from the EV fleets to the balance of wind power inputs.

If the additional annual electricity demand to operate the BEV and HFCV fleets in the scenarios is to be generated from Danish offshore wind turbines the corresponding wind power capacity increase will be as shown in Figure 6-4.

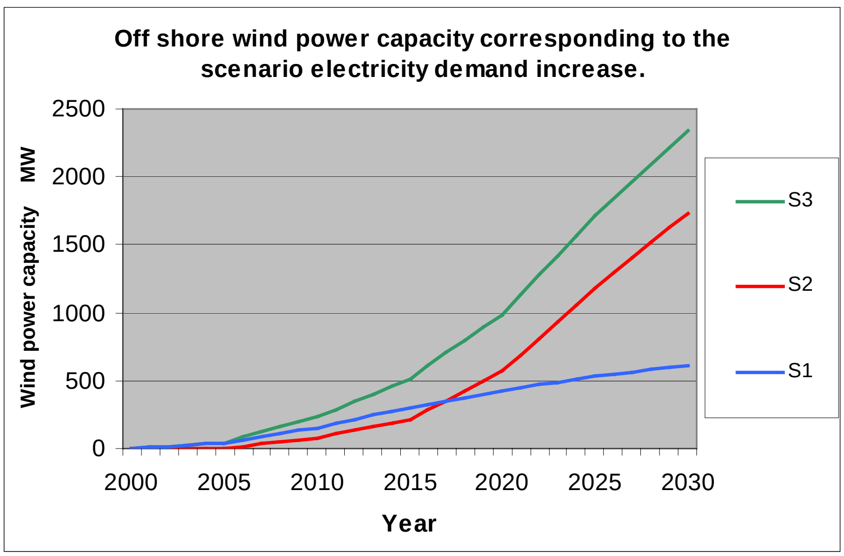

Figure 6-4 Wind power capacity offshore, able to produce the energy equivalent of the electricity demand increase resulting from the scenarios S1, S2, and S3.

The offshore wind power capacity covering this increased demand has been calculated based on the assumption of a capacity factor of 3300 hours/year (full load hours). Transmission and distribution losses have been set at 6%.

The corresponding wind power capacity needed to produce the electricity associated with operating the individual (average fleet) electric vehicle on an annual basis is shown in Table 6-1.

Table 6-1 Wind power capacity needed to generate the energy, equivalent to the annual demand of the average, electricity based vehicle. Assumed that electricity for transport is generated from offshore wind power.

Wind capacity per vehicle	**S1**	**S2**	**S3**
	kW/car	kW/car	kW/car
2005	1.44	..	1.44
2015	0.90	2.26	1.19
2030	0.66	1.77	1.23

From the table it is seen, that the average BEV vehicle year 2030 on an annual basis consumes electricity equivalent to the production from approximately 0.66 kW installed wind power capacity offshore. Hydrogen to serve the corresponding size HFCV vehicle could be produced from the electricity generated by approximately 1.8 kW of installed wind power capacity, in Danish offshore wind conditions.

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Title and authors

Electric vehicles and renewable energy in the transport sector – energy system consequences

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Abstract (max. 2000 characters)

The aim of the project is to analyse energy, environmental and economic aspects of integrating electric vehicles in the future Danish energy system. Consequences of large-scale utilisation of electric vehicles are analysed. The aim is furthermore to illustrate the potential synergistic interplay between the utilisation of electric vehicles and large-scale utilisation of fluctuating renewable energy resources, such as wind power. Economic aspects for electric vehicles interacting with a liberalised electricity market are analysed. The project focuses on battery electric vehicles and fuel cell vehicles based on hydrogen.

Based on assumptions on the future technical development for battery electric vehicles, fuel cell vehicles on hydrogen, and for the conventional internal combustion engine vehicles, scenarios are set up to reflect expected options for the long-term development of road transport vehicles.

Focus is put on the Danish fleet of passenger cars and delivery vans. The scenario analysis includes assumptions on market potential developments and market penetration for the alternative vehicles. Vehicle replacement rates in the Danish transport fleet and the size of fleet development are based on data from The Danish Road Directorate. The electricity supply system development assumed is based on the Danish energy plan, Energy 21, The Plan scenario. The time horizon of the analysis is year 2030.

Results from the scenario analysis include the time scales involved for the potential transition towards electricity based vehicles, the fleet composition development, the associated developments in transport fuel consumption and fuel substitution, and the potential CO_2-emission reduction achievable in the overall transport and power supply system.

Detailed model simulations, on an hourly basis, have furthermore been carried out for year 2005 that address potential electricity purchase options for electric vehicles in the context of a liberalised electricity market. The baseline electricity market considered comprises a spot market and a balance market. The structure chosen for the baseline spot market is close to the structure of the Nord Pool electricity market, and the structure of the balance or regulatory market is close to the Norwegian model.

Descriptors INIS/EDB

TRANSPORTATION SECTOR; ROAD TRANSPORT; CARBON DIOXIDE; SECTORAL ANALYSIS; ELECTRIC-POWERED VEHICLES; HYDROGEN; HYDROGEN FUEL CELLS; TECHNOLOGY ASSESSMENT; DENMARK; SYSTEMS ANALYSIS; ENERGY SYSTEMS; ENERGY CONSUMPTION; WIND POWER; ELECTRIC POWER; ENERGY SUPPLIES; FORECASTING; COMPUTERIZED; SIMULATION; ELECTRIC UTILITIES; MARKET; POWER GENERATION; ENERGY SUPPLIES; POWER TRANSMISSION; REGULATIONS; EUROPE; SPOT MARKET.

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